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Fan

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(54) **APPARATUS AND METHODS FOR DIGITAL SIGNAL CONSTELLATION TRANSFORMATION**

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Related U.S. Application Data

(63) Continuation of application No. 15/130,778, filed on Apr. 15, 2016, now Pat. No. 9,853,734.

(60) Provisional application No. 62/148,688, filed on Apr. 16, 2015.

(51) **Int. Cl.**
H04B 10/40 (2013.01)
H04B 10/61 (2013.01)

(52) **U.S. Cl.**
CPC ***H04B 10/40*** (2013.01); ***H04B 10/6165*** (2013.01); *H04B 2210/252* (2013.01)

(58) **Field of Classification Search**
CPC H04B 10/40; H04B 10/6165; H04B 2210/252
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,623,797 B2 * 11/2009 Crivelli H04B 10/6971 375/233
8,041,233 B2 * 10/2011 Hueda H04B 10/60 398/140
8,116,367 B2 * 2/2012 Carrer H04L 25/03063 375/233
8,488,726 B2 * 7/2013 Hueda H04L 25/03292 375/136

(Continued)

OTHER PUBLICATIONS

Hwan Seok Chung et al., "Field trial of automatic bias control scheme for optical IQ modulator and demodulator with directly detected 112 Gb/s DQPSK Signal", Optics Express, Oct. 21, 2013 pp. 24962-24968, vol. 21, No. 21, Optical Society of America.

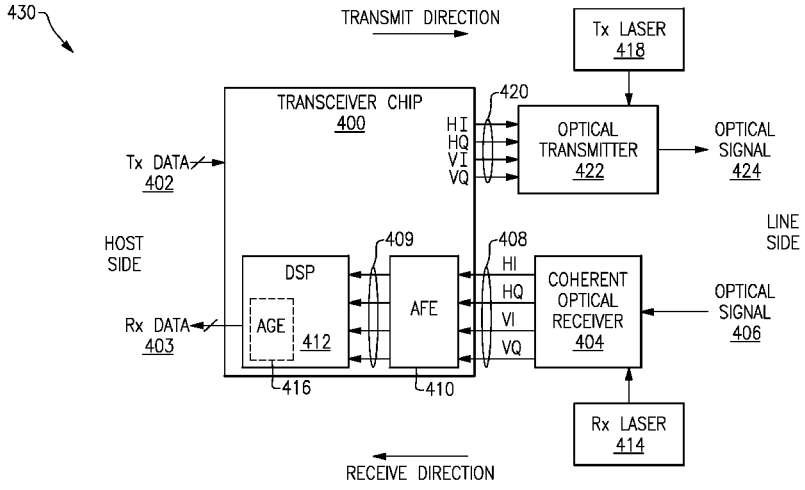
(Continued)

Primary Examiner — Danny Leung
(74) *Attorney, Agent, or Firm* — Richard T. Ogawa; Ogawa P.C.

(57) **ABSTRACT**

Apparatus and method for digital signal constellation transformation are provided herein. In certain configurations, an integrated circuit includes an analog front-end that converts an analog signal vector representing an optical signal into a digital signal vector, and a digital signal processing circuit that processes the digital signal vector to recover data from the optical signal. The digital signal processing circuit generates signal data representing a signal constellation of the digital signal vector. The digital signal processing circuit includes an adaptive gain equalizer that compensates the signal data for distortion of the signal constellation arising from biasing errors of optical modulators used to transmit the optical signal.

32 Claims, 14 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

8,565,297	B2	10/2013	Carrer et al.	
8,761,609	B1 *	6/2014	Agazzi	H04B 10/616 398/155
8,873,974	B2	10/2014	Hueda et al.	
8,886,055	B1 *	11/2014	Morero	H04L 1/0041 398/192
9,071,364	B1 *	6/2015	Voois	H04B 10/58
9,306,676	B1 *	4/2016	Castrillon	H04B 10/6165
9,337,934	B1 *	5/2016	Agazzi	H04B 10/61
9,391,715	B1	7/2016	Agazzi et al.	
9,496,967	B1	11/2016	Castrillon et al.	
9,853,734	B1 *	12/2017	Fan	H04B 10/40
2005/0068612	A1 *	3/2005	Wilson	H01S 3/1301 359/337
2010/0266291	A1 *	10/2010	Boffi	H04B 10/61 398/159
2013/0259112	A1 *	10/2013	Bae	H04L 25/03891 375/232
2015/0089330	A1 *	3/2015	Xia	G06F 11/1008 714/773
2015/0171971	A1 *	6/2015	Enoki	H04B 10/5053 398/183
2017/0338893	A1 *	11/2017	Cavaliere	H04B 10/616

OTHER PUBLICATIONS

Hiroto Kawakami et al., "Auto Bias Control Technique Based on Asymmetric Bias Dithering for Optical QPSK Modulation", Journal of Lightwave Technology, Apr. 1, 2012, pp. 962-968, vol. 30, No. 7, IEEE.

* cited by examiner

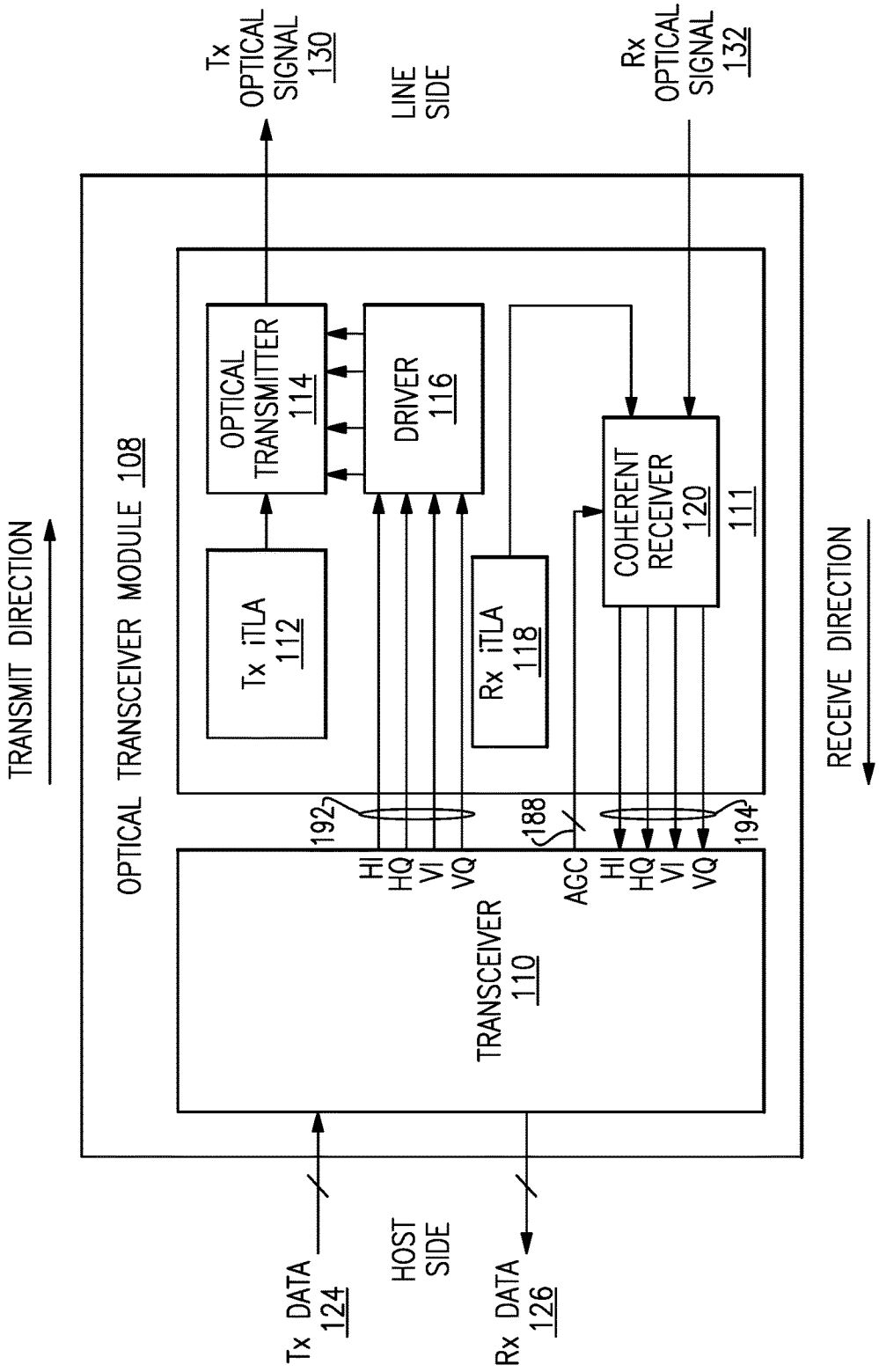

Tx OPTICAL SIGNAL 130
LINE SIDE
Rx OPTICAL SIGNAL 132
TRANSMIT DIRECTION
OPTICAL TRANSCEIVER MODULE 108
OPTICAL TRANSMITTER 114
DRIVER 116
Tx iTLA 112
Rx iTLA 118
COHERENT RECEIVER 120
111
RECEIVE DIRECTION
192
188
194
HI
HQ
VI
VQ
AGC
HI
HQ
VI
VQ
TRANSCEIVER 110
Tx DATA 124
HOST SIDE
Rx DATA 126

FIG.1

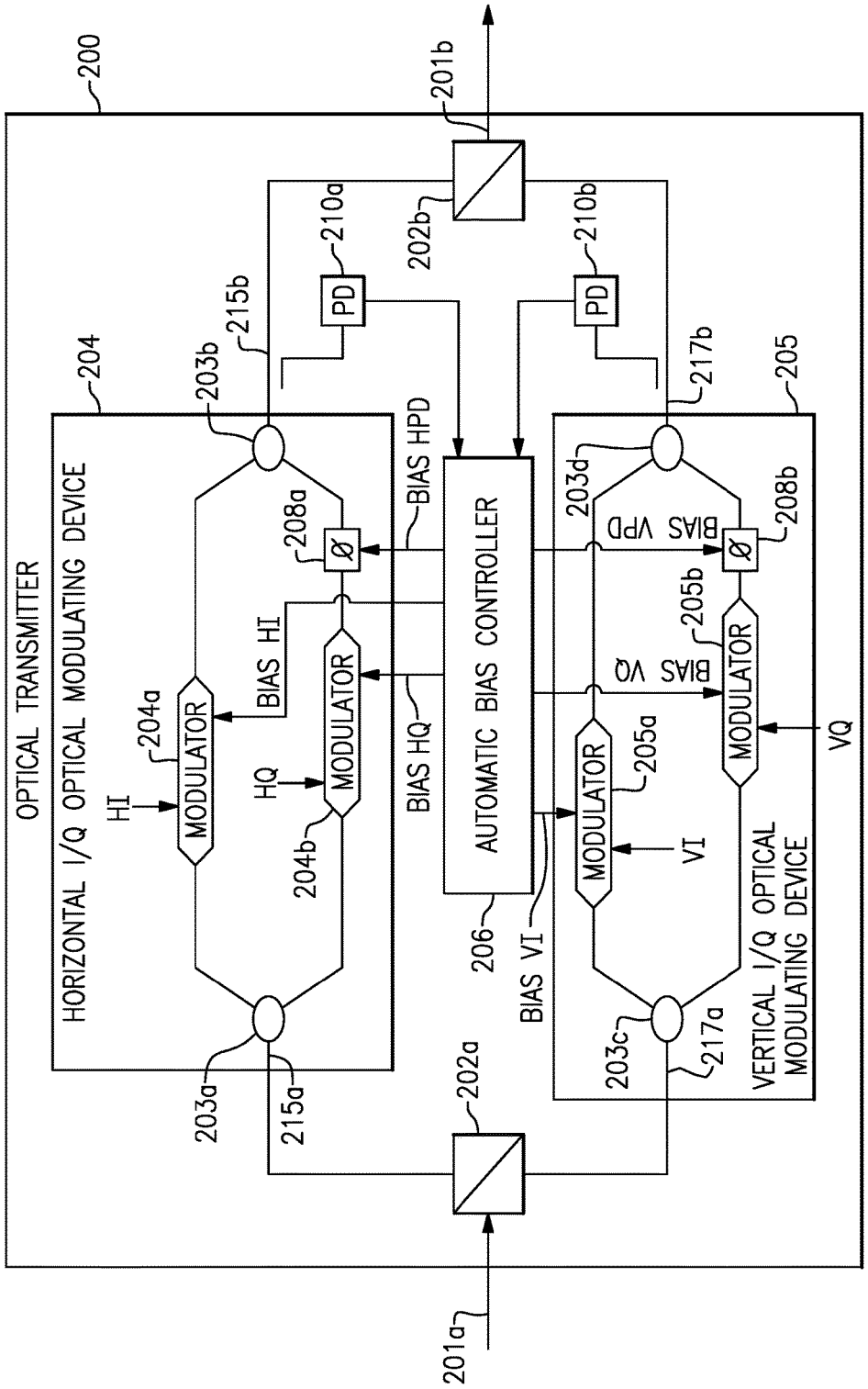

200
OPTICAL TRANSMITTER
HORIZONTAL I/Q OPTICAL MODULATING DEVICE
VERTICAL I/Q OPTICAL MODULATING DEVICE
AUTOMATIC BIAS CONTROLLER
MODULATOR
PD
BIAS HI
BIAS HQ
BIAS VI
BIAS VQ
BIAS HPD
BIAS VPD
HI
HQ
VI
VQ
201a
201b
202a
202b
203a
203b
203c
203d
204
204a
204b
205
205a
205b
206
208a
208b
210a
210b
215a
215b
217a
217b

FIG.2

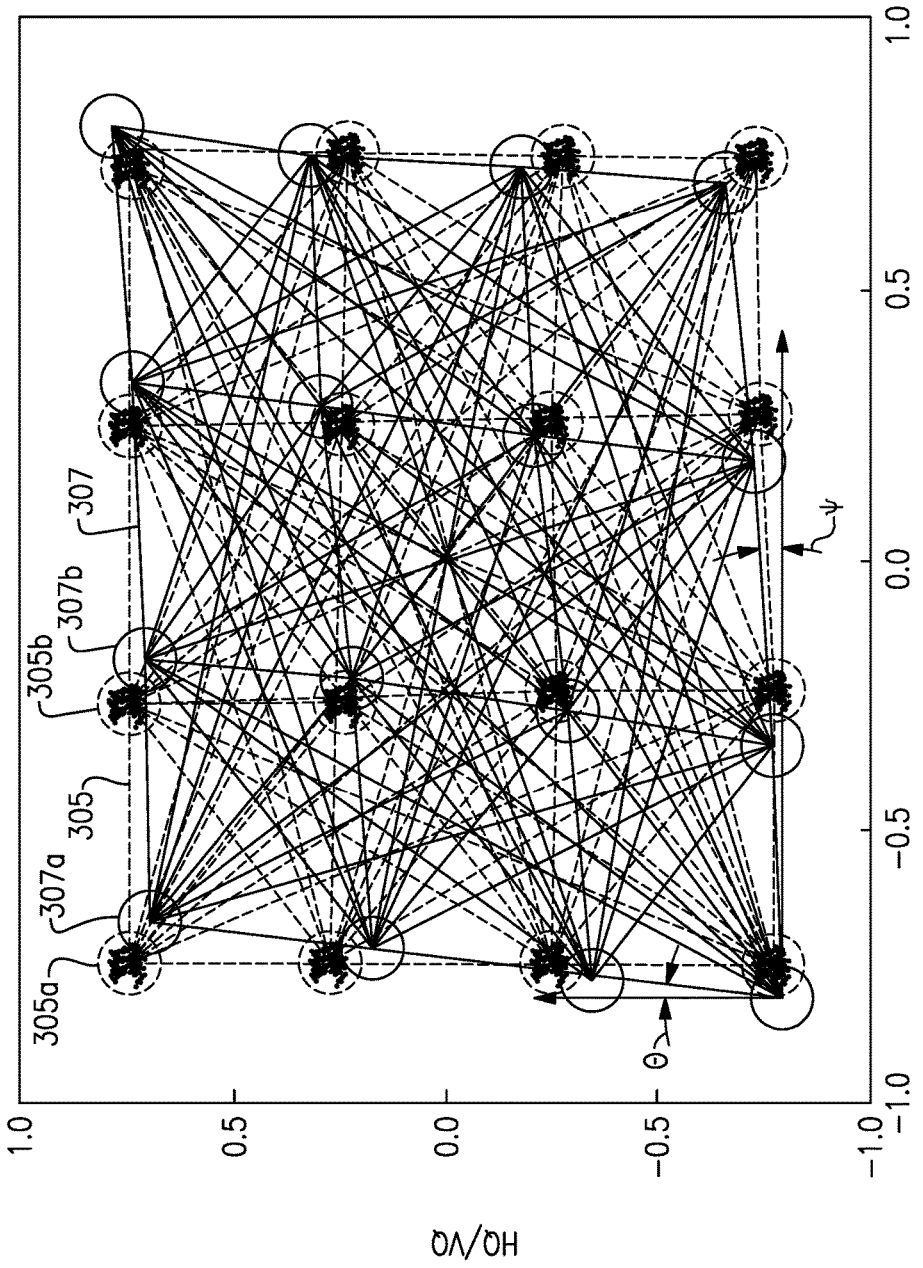


FIG.3A

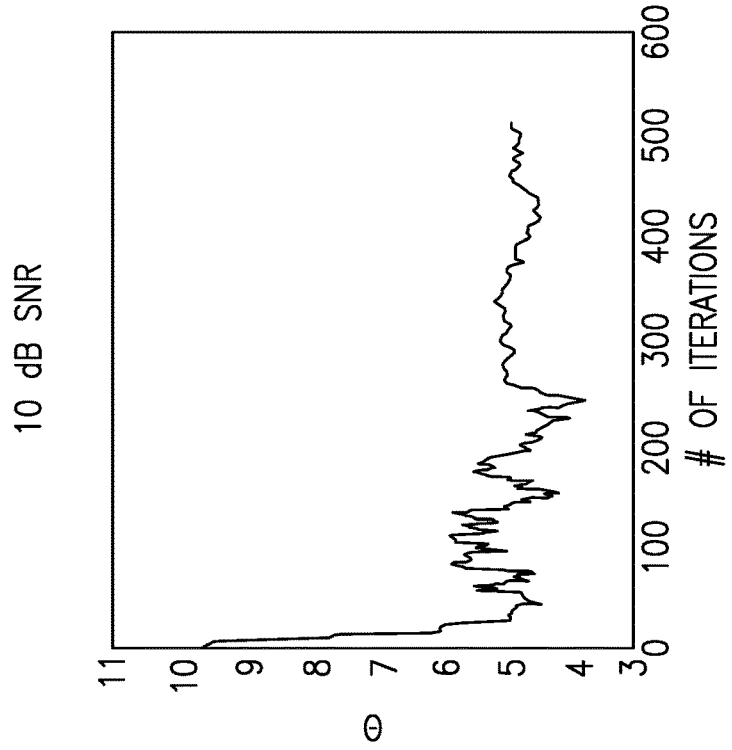

10 dB SNR
Θ
OF ITERATIONS
11
10
9
8
7
6
5
4
3
0
100
200
300
400
500
600

FIG.3C

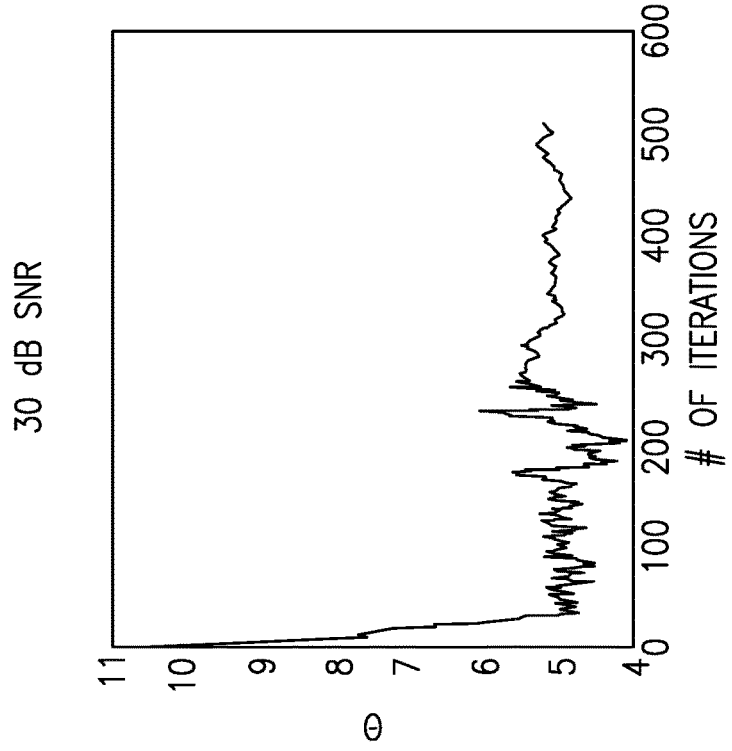

30 dB SNR
Θ
OF ITERATIONS
11
10
9
8
7
6
5
4
0
100
200
300
400
500
600

FIG.3B

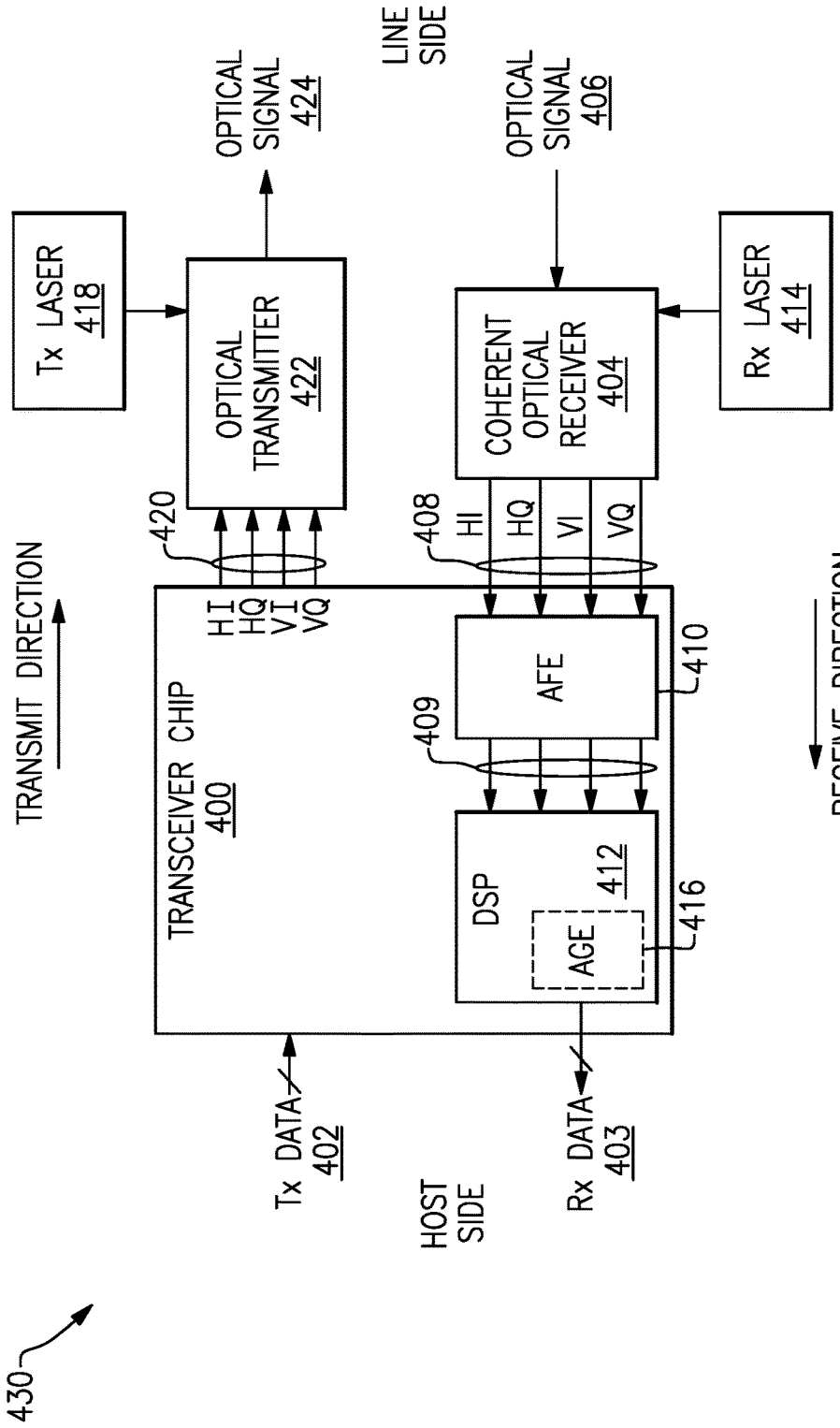

LINE SIDE
OPTICAL SIGNAL 424
OPTICAL SIGNAL 406
Tx LASER 418
OPTICAL TRANSMITTER 422
COHERENT OPTICAL RECEIVER 404
Rx LASER 414
420
408
HI
HQ
VI
VQ
TRANSMIT DIRECTION
RECEIVE DIRECTION
TRANSCEIVER CHIP 400
AFE
410
409
DSP
412
AGE
416
Tx DATA 402
Rx DATA 403
HOST SIDE
430

FIG.4A

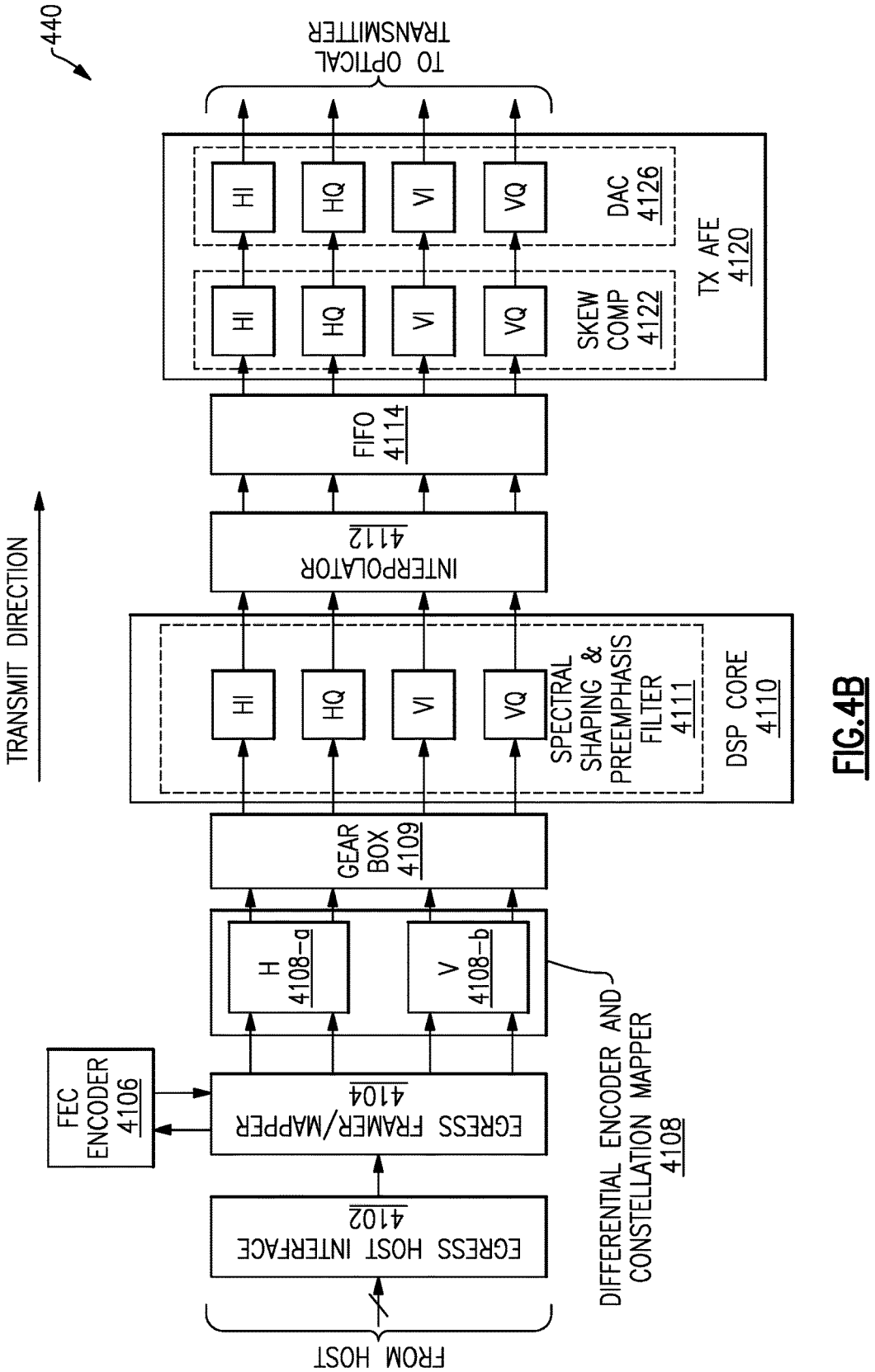

440
TO OPTICAL TRANSMITTER
HI
HQ
VI
VQ
DAC 4126
SKEW COMP 4122
TX AFE 4120
FIFO 4114
INTERPOLATOR 4112
SPECTRAL SHAPING & PREEMPHASIS FILTER 4111
DSP CORE 4110
TRANSMIT DIRECTION
GEAR BOX 4109
H 4108-a
V 4108-b
DIFFERENTIAL ENCODER AND CONSTELLATION MAPPER 4108
FEC ENCODER 4106
EGRESS FRAMER/MAPPER 4104
EGRESS HOST INTERFACE 4102
FROM HOST

FIG.4B

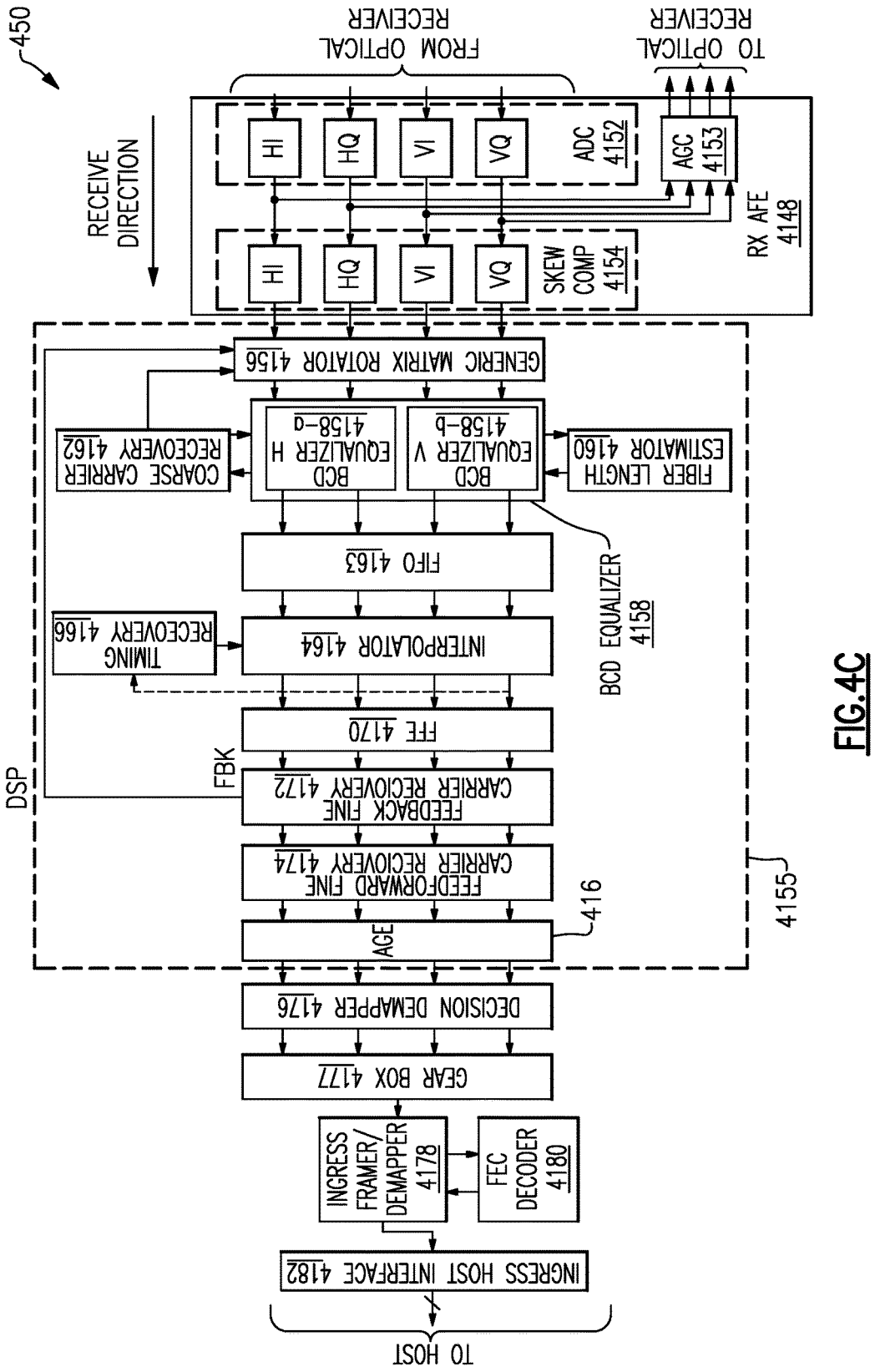

450
FROM OPTICAL RECEIVER
TO OPTICAL RECEIVER
RECEIVE DIRECTION
HI
HQ
VI
VQ
ADC 4152
AGC 4153
SKEW COMP 4154
RX AFE 4148
GENERIC MATRIX ROTATOR 4156
BCD EQUALIZER H 4158-a
BCD EQUALIZER V 4158-b
COARSE CARRIER RECEOVERY 4162
FIBER LENGTH ESTIMATOR 4160
BCD EQUALIZER 4158
FIFO 4163
TIMING RECEOVERY 4166
INTERPOLATOR 4164
FFE 4170
FBK
FEEDBACK FINE CARRIER RECIOVERY 4172
FEEDFORWARD FINE CARRIER RECIOVERY 4174
AGE
416
DSP
4155
DECISION DEMAPPER 4176
GEAR BOX 4177
INGRESS FRAMER/ DEMAPPER 4178
FEC DECODER 4180
INGRESS HOST INTERFACE 4182
TO HOST

FIG.4C

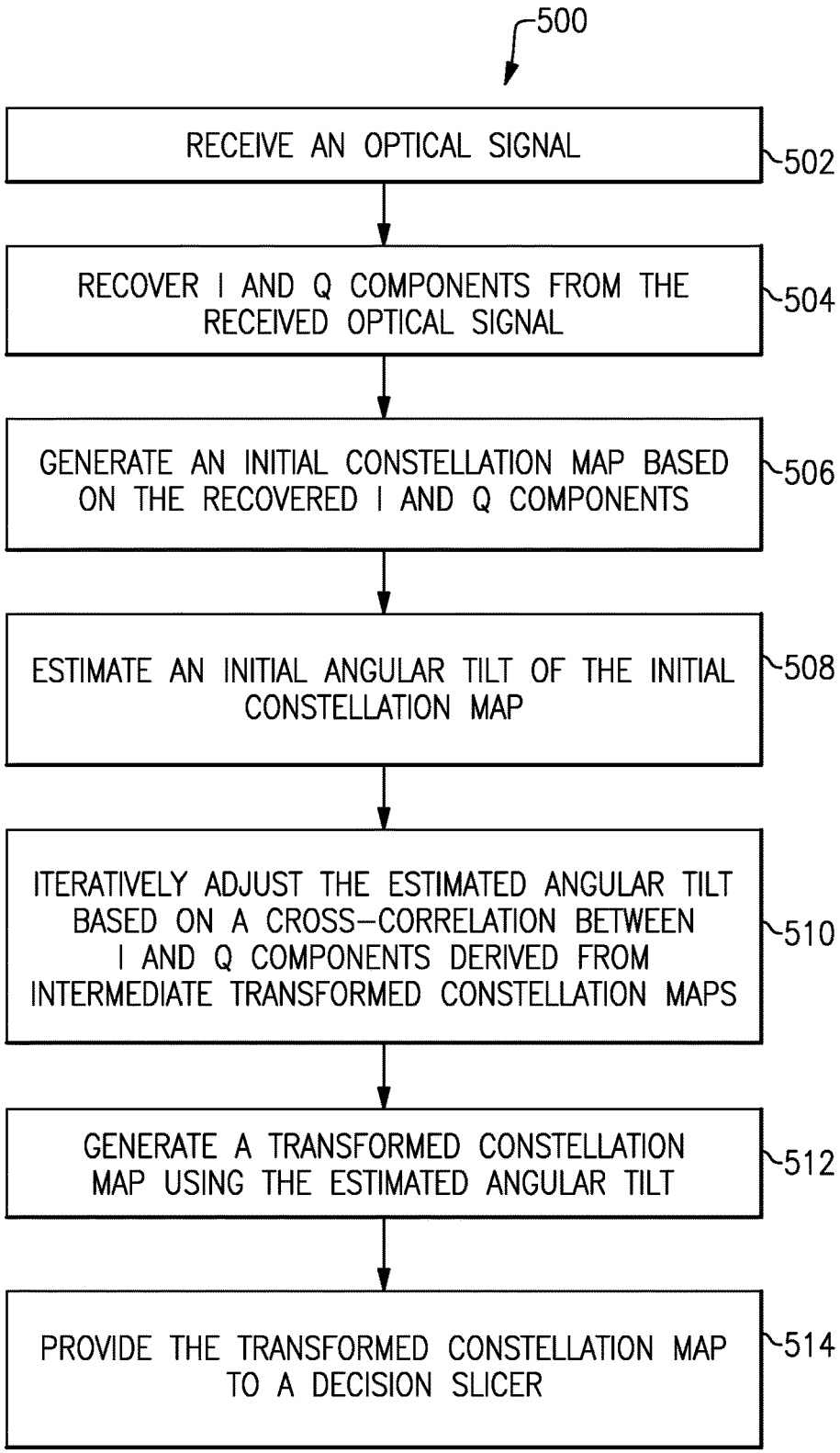

500
RECEIVE AN OPTICAL SIGNAL
502
RECOVER I AND Q COMPONENTS FROM THE RECEIVED OPTICAL SIGNAL
504
GENERATE AN INITIAL CONSTELLATION MAP BASED ON THE RECOVERED I AND Q COMPONENTS
506
ESTIMATE AN INITIAL ANGULAR TILT OF THE INITIAL CONSTELLATION MAP
508
ITERATIVELY ADJUST THE ESTIMATED ANGULAR TILT BASED ON A CROSS-CORRELATION BETWEEN I AND Q COMPONENTS DERIVED FROM INTERMEDIATE TRANSFORMED CONSTELLATION MAPS
510
GENERATE A TRANSFORMED CONSTELLATION MAP USING THE ESTIMATED ANGULAR TILT
512
PROVIDE THE TRANSFORMED CONSTELLATION MAP TO A DECISION SLICER
514

FIG.5

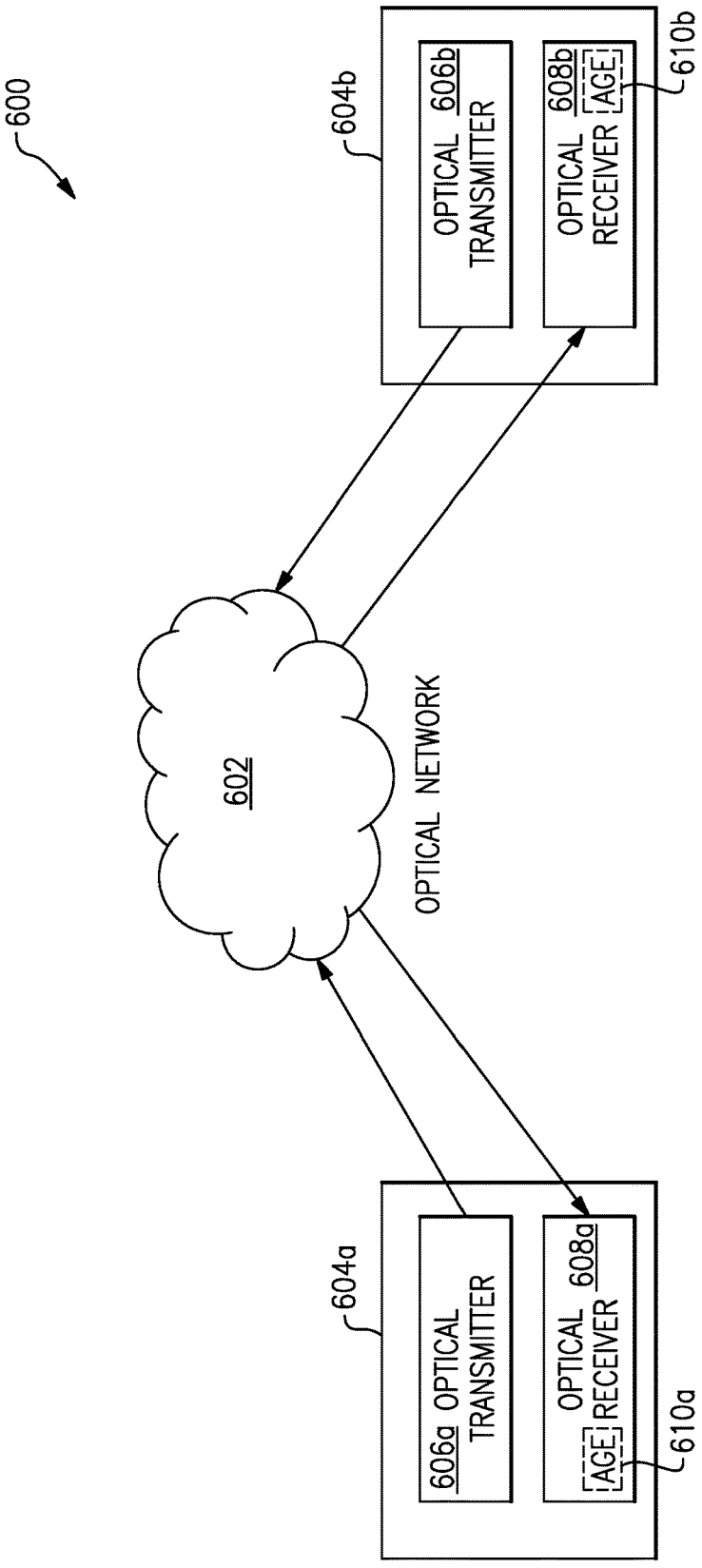

600
604b
OPTICAL TRANSMITTER 606b
OPTICAL RECEIVER [AGE] 608b
610b
602
OPTICAL NETWORK
604a
606a OPTICAL TRANSMITTER
OPTICAL RECEIVER [AGE] 608a
610a

FIG.6

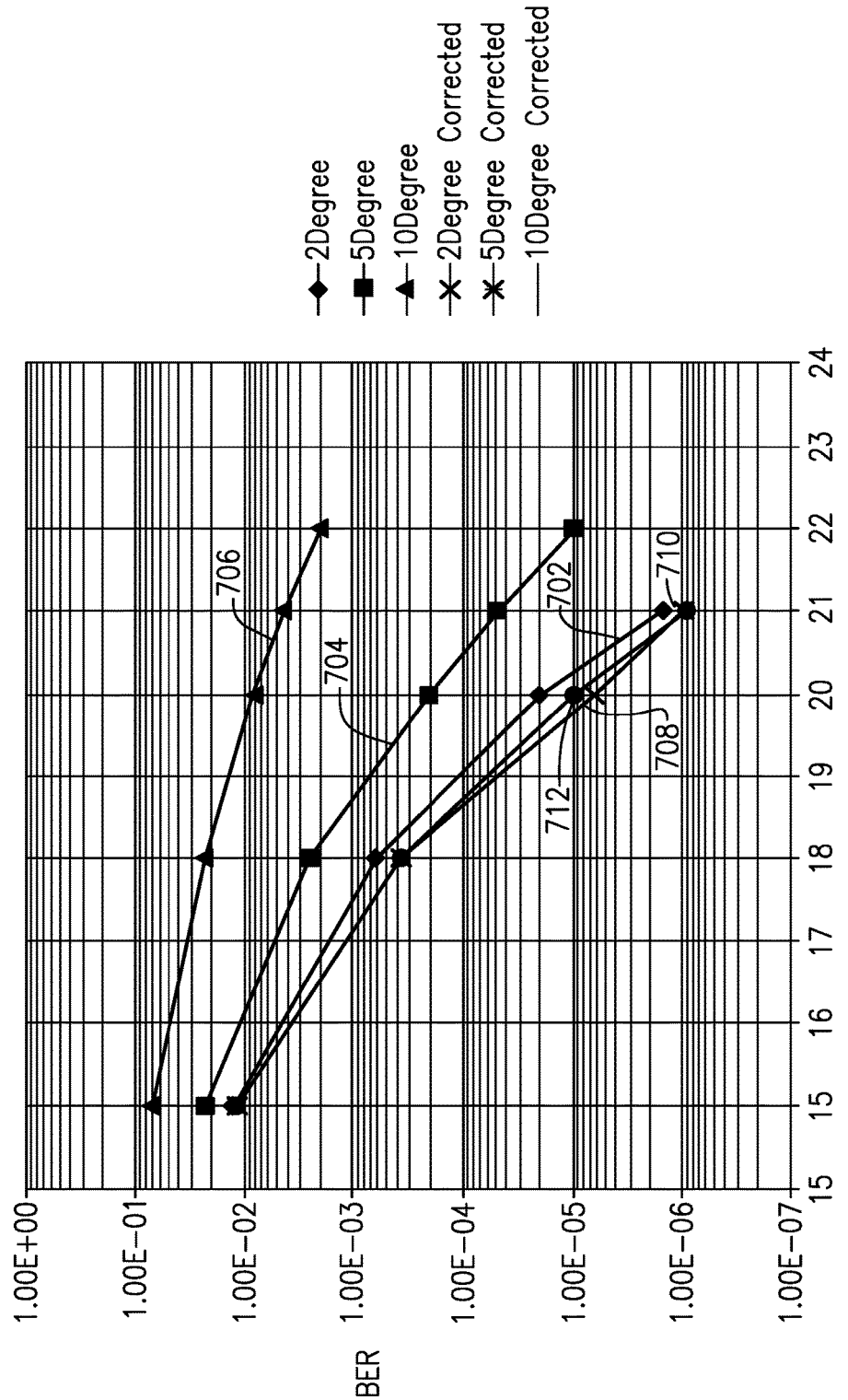

2Degree
5Degree
10Degree
2Degree Corrected
5Degree Corrected
10Degree Corrected
706
704
702
710
708
712
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
BER
15
15
16
17
18
19
20
21
22
23
24
SNR

FIG.7

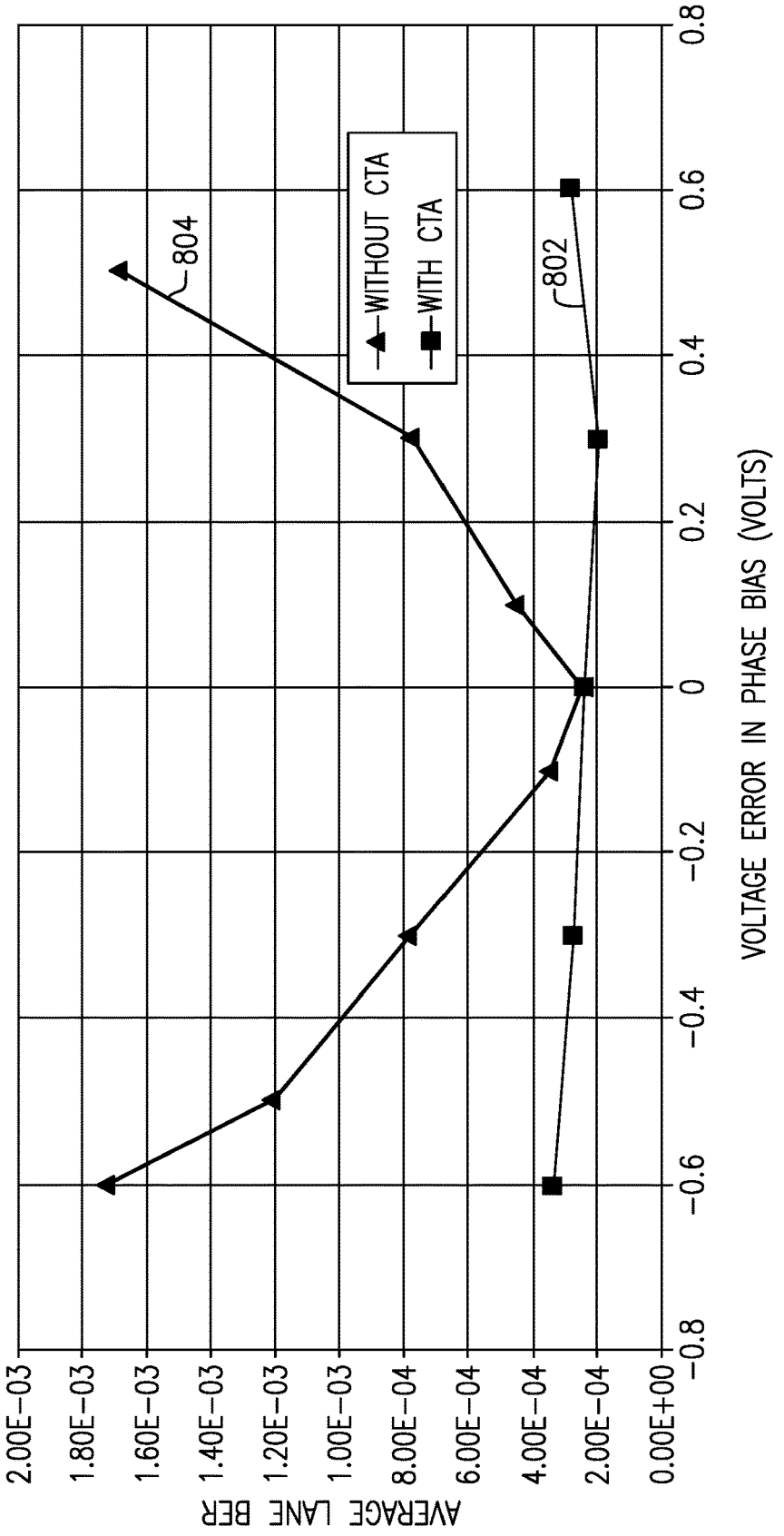

AVERAGE LANE BER
2.00E−03
1.80E−03
1.60E−03
1.40E−03
1.20E−03
1.00E−03
8.00E−04
6.00E−04
4.00E−04
2.00E−04
0.00E+00
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
VOLTAGE ERROR IN PHASE BIAS (VOLTS)
WITHOUT CTA
WITH CTA
804
802

FIG.8

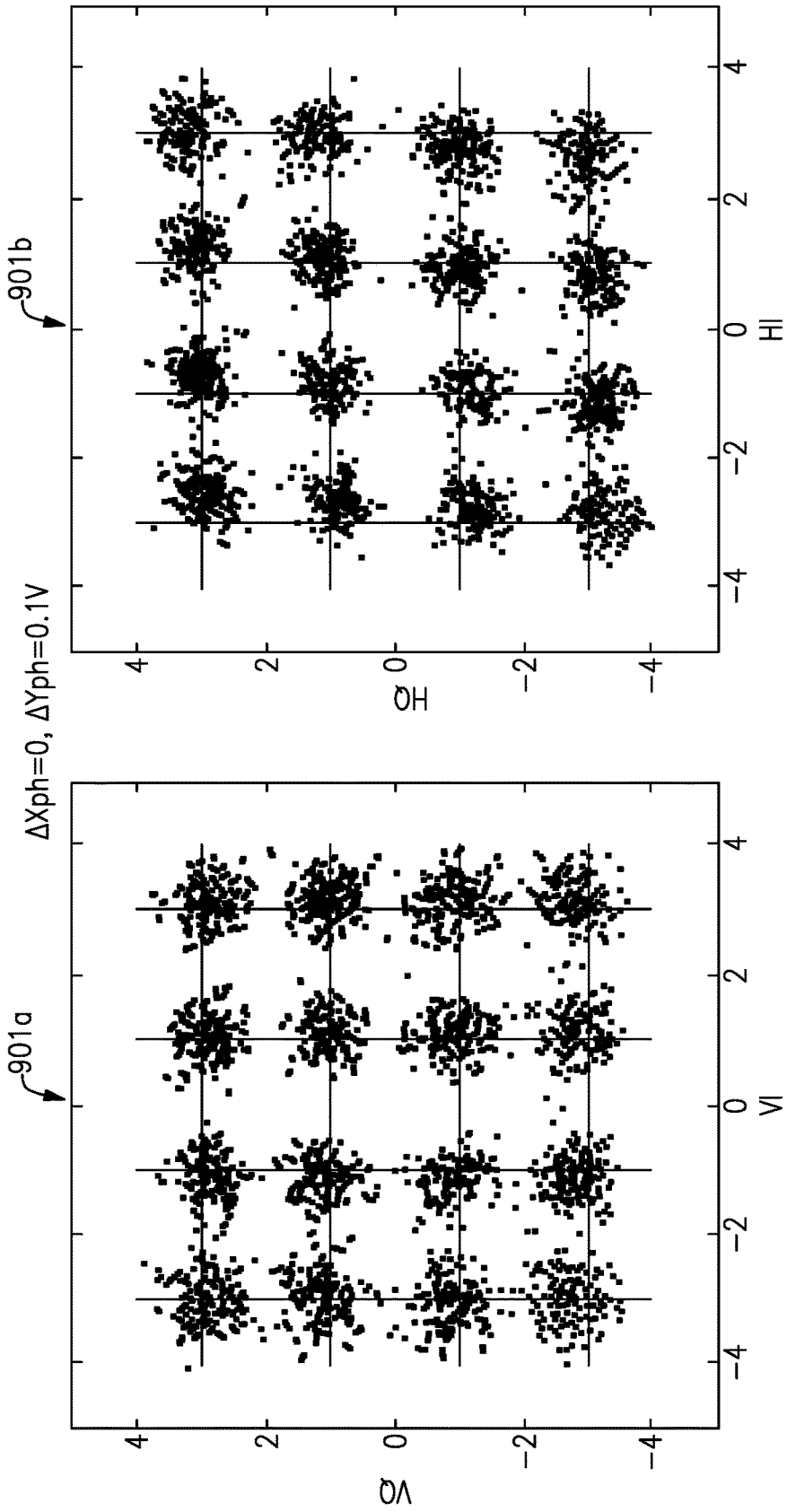


FIG.9A

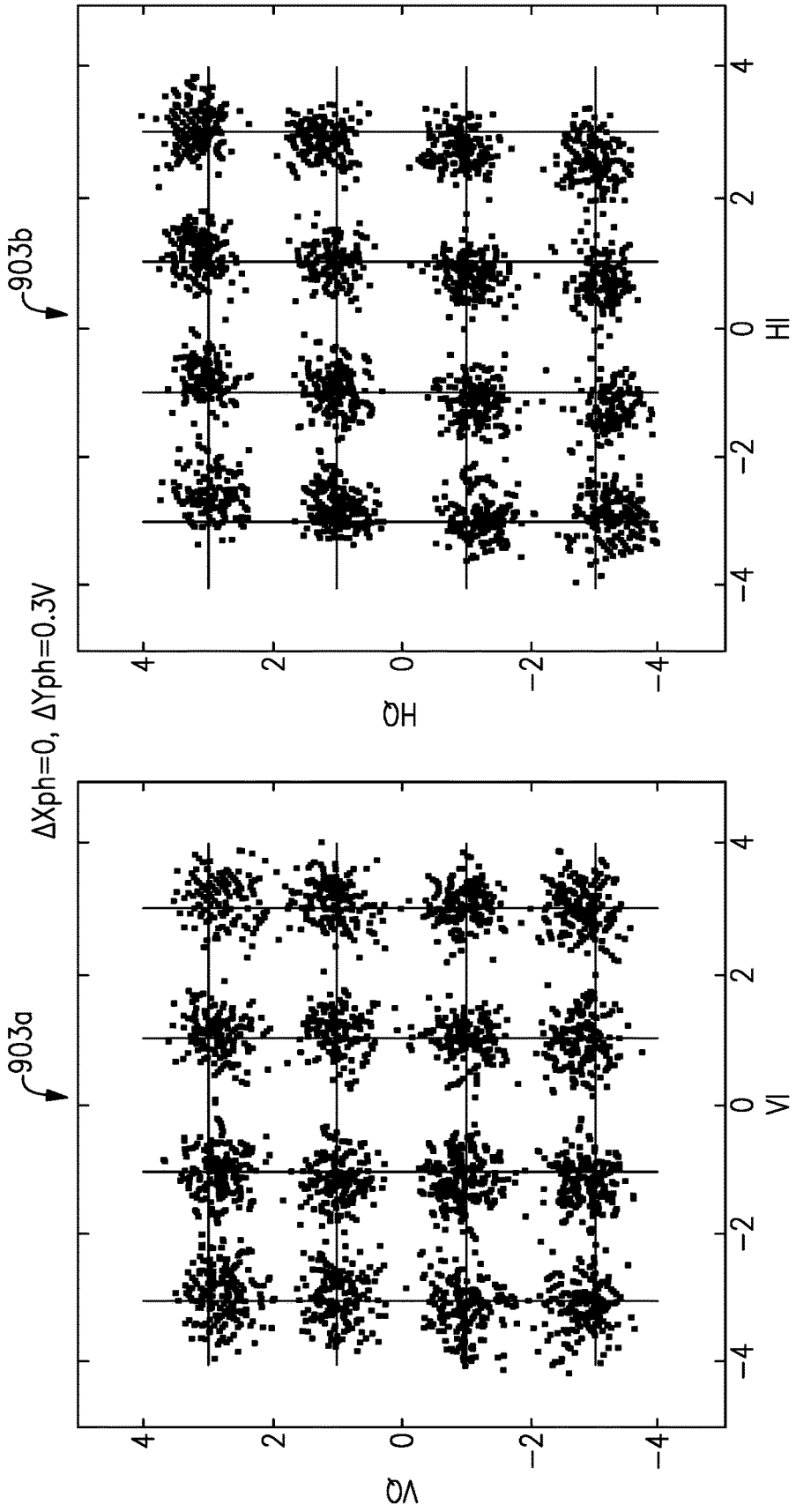


FIG.9B

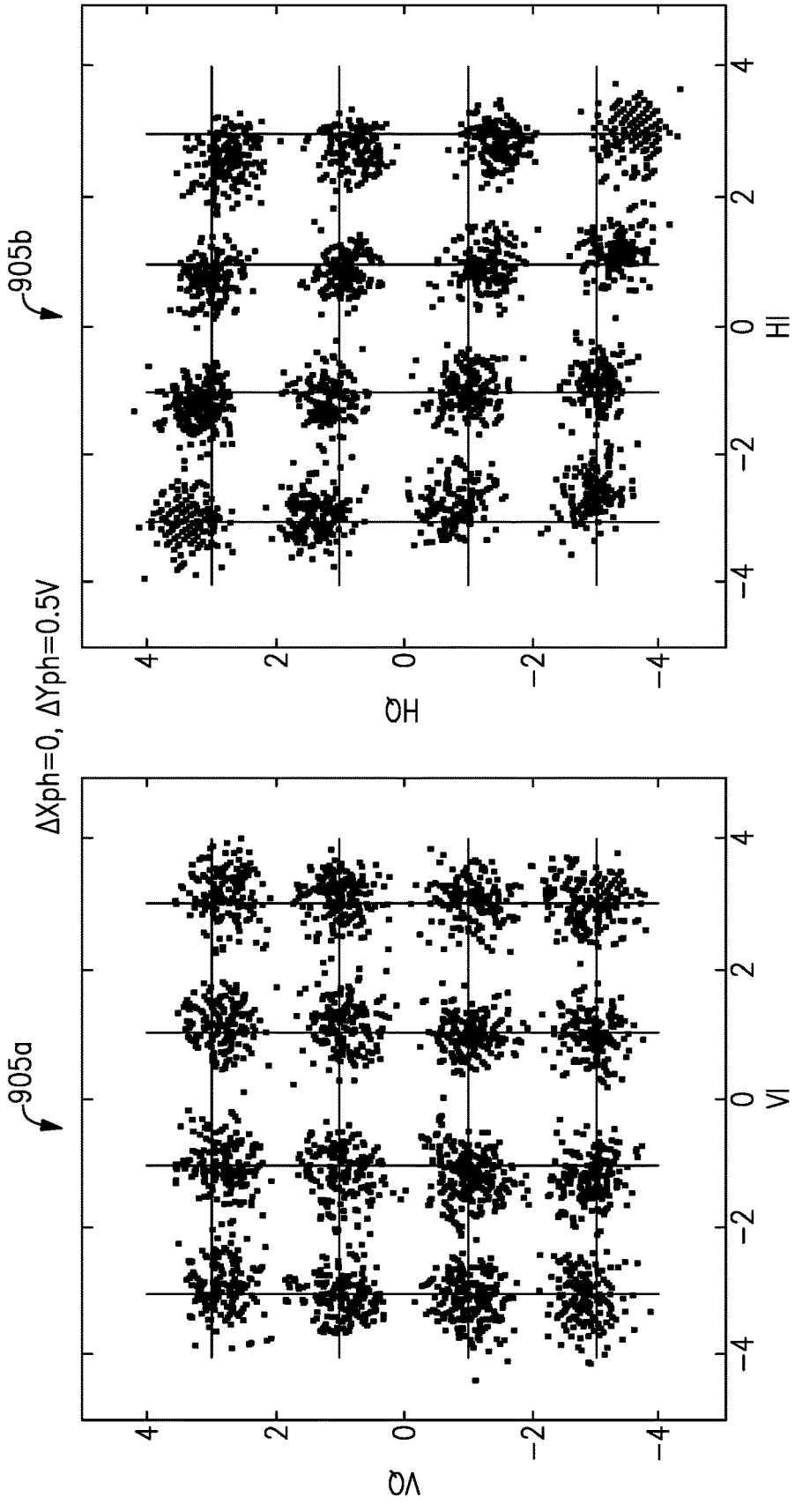


FIG.9C

APPARATUS AND METHODS FOR DIGITAL SIGNAL CONSTELLATION TRANSFORMATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of and incorporates by reference, for all purposes, U.S. patent application Ser. No. 15/130,778, filed Apr. 15, 2016. U.S. patent application Ser. No. 15/130,778 which claims priority to U.S. Provisional Patent Application No. 62/148,688, filed Apr. 16, 2015, incorporated herein by reference in its entirety for all purposes.

BACKGROUND

Field

This disclosure relates to methods and systems for high-speed optical communications.

Description of the Related Technology

There has been widespread adoption of personal electronic devices including smart phones, tablets, notebooks, laptops, digital camera, video recorders, gaming systems, etc. These devices are being used to communicate ever-increasing quantities of data, such as between different personal electronic devices, between personal electronic devices and peripheral devices (for example, display devices, external storage devices, etc.), and the like.

Enormous data communication demands are also present in a variety of other contexts. For example, data centers are communicating ever-increasing amounts of data, and also require fast and reliable data communication between devices. The various methods and systems disclosed herein provide various improvements and benefits vis-à-vis existing high-speed communication technologies.

SUMMARY

An innovative aspect of the subject matter disclosed herein is implemented in an integrated circuit comprising an analog front-end configured to convert an analog signal vector representing an optical signal into a digital signal vector; and a digital signal processing circuit configured to generate signal data representing a signal constellation of the digital signal vector. The digital signal vector comprises a digital representation of an in-phase (I) component and a quadrature-phase (Q) component of the optical signal. The digital signal processing circuit comprises an adaptive gain equalizer configured to generate transformed signal data by compensating the signal data for distortion of the signal constellation.

In various embodiments of the integrated circuit, the adaptive gain equalizer can be configured to generate an estimate of an angular tilt of the signal constellation and to compensate the signal data based on the estimate of the angular tilt. The adaptive gain equalizer can be configured to generate the estimate of the angular tilt based on a sum of a plurality of cross-correlations of I and Q components of the signal constellation. The sum of the plurality of cross-correlations can be computed over a moving window of data samples obtained from the digital signal vector. The adaptive gain equalizer can be configured to iteratively revise the estimate of the angular tilt until I and Q components of the transformed signal data are substantially uncorrelated. The adaptive gain equalizer can be configured to iteratively revise the estimate of the angular tilt based on a step gain that changes based on a number of times the angular tilt has been estimated. The adaptive gain equalizer can be configured to generate the transformed signal data based on a transformation matrix that includes the estimate of the angular tilt.

In various embodiments of the integrated circuit, the digital signal processing circuit can be configured to process the signal data for at least one of feed forward equalization or carrier recovery prior to compensating the signal data for distortion of the signal constellation. Various embodiments of the integrated circuit can further comprise a decision slicer configured to slice the transformed signal data. The distortion of the signal constellation can comprise at least one of squeezing, shifting, or tilting. In various embodiments, the optical signal can comprise a multi-level quadrature amplitude modulation (QAM) signal, a discrete multi-toned (DMT) modulation signal, an orthogonal frequency division multiplexing (OFDM), or a phase-shift keying (PSK) signal (including, but not limited to, a quadrature phase-shift keying (QPSK) signal).

Another innovative aspect of the subject matter disclosed herein is implemented in a method of digital signal constellation transformation in an optical communication device. The method comprises receiving an optical signal as an input to a coherent optical receiver; generating an analog signal vector representing the optical signal using the coherent optical receiver; converting the analog signal vector into a digital signal vector using an analog front-end; generating signal data representing a signal constellation of the digital signal vector using a digital signal processing circuit; and compensating the signal data for distortion of the signal constellation using an adaptive gain equalizer of the digital signal processing circuit. The digital signal vector comprises a digital representation of an in-phase (I) component and a quadrature-phase (Q) component of the optical signal.

In various embodiments of the method compensating the signal data for distortion can comprise generating an estimate of an angular tilt of the signal constellation and compensating the signal data based on the estimate of the angular tilt. The method can further comprise transforming the signal data based on a transformation matrix that includes the estimate of the angular tilt. In various embodiments of the method, generating the estimate of the angular tilt can comprise summing a plurality of cross-correlations of I and Q components of the signal constellation. The method can further comprise iteratively revising the estimate of the angular tilt. Various embodiments of the method can further comprise processing the signal data for at least one of feed forward equalization or carrier recovery prior to compensating the signal data for distortion of the signal constellation.

Yet another innovative aspect of the subject matter disclosed herein is implemented in an integrated optical module comprising a coherent optical receiver; and a transceiver. The coherent optical receiver is configured to receive an optical signal from an optical cable and generate an analog signal vector representing the optical signal. The transceiver is configured to process the analog signal vector to generate a digital signal vector comprising a digital representation of an in-phase (I) component and a quadrature-phase (Q) component of the optical signal. The transceiver is further configured to generate signal data representing a signal constellation of the digital signal vector. The transceiver comprises an adaptive gain equalizer configured to generate

transformed signal data by compensating the signal data for distortion of the signal constellation.

In various embodiments of the integrated optical module, the adaptive gain equalizer can be configured to generate an estimate of an angular tilt of the signal constellation and to compensate the signal data based on the estimate of the angular tilt. The adaptive gain equalizer can be configured to generate the estimate of the angular tilt based on a sum of a plurality of cross-correlations of I and Q components of the signal constellation. The adaptive gain equalizer can be configured to iteratively revise the estimate of the angular tilt until I and Q components of the transformed signal data are substantially uncorrelated. The adaptive gain equalizer can provide separate distortion compensation for a first portion of the signal data associated with a horizontal polarization of the optical signal and for a second portion of the signal data associated with a vertical polarization of the optical signal.

An innovative aspect of the subject matter disclosed herein is implemented in an optical communication system comprising an optical transmitter configured to provide optical transmissions over an optical network; an optical receiver configured to receive an optical signal over the from the optical network and to generate an analog signal vector representing the optical signal; and a transceiver coupled to the optical transmitter and to the optical receiver. The transceiver comprises an analog front-end; and a digital signal processing circuit. The analog front-end is configured to convert the analog signal vector into a digital signal vector, wherein the digital signal vector comprises a digital representation of an in-phase (I) component and a quadrature-phase (Q) component of the optical signal configured to generate signal data representing a signal constellation of the digital signal vector. The digital signal processing circuit comprises an adaptive gain equalizer configured to generate transformed signal data by compensating the signal data for distortion of the signal constellation.

In various embodiments of the optical communication system, the adaptive gain equalizer can be configured to generate an estimate of an angular tilt of the signal constellation and to compensate the signal data based on the estimate of the angular tilt. The optical transmitter can comprise one or more modulators and an automatic bias controller configured to bias the one or more modulators.

BRIEF DESCRIPTION OF THE DRAWINGS

Example implementations disclosed herein are illustrated in the accompanying schematic drawings, which are for illustrative purposes only.

FIG. **1** is a schematic diagram of one embodiment of an optical transceiver module.

FIG. **2** is a schematic diagram of an optical transmitter that can be employed to generate spectrally efficient optical signals.

FIG. **3**A is a graph of two examples of constellation maps formed by the symbols of a 16-level QAM signal.

FIGS. **3**B and **3**C are two examples of plots illustrating convergence of tilt angle as a function of the number of iterations for different signal-to-noise ratio (SNR) levels.

FIG. **4**A is a schematic diagram of an optical transceiver system including a transceiver chip according to one embodiment.

FIG. **4**B is a schematic diagram of one embodiment of a transmit path architecture for the transceiver chip of FIG. **4**A.

FIG. **4**C is a schematic diagram of one embodiment of a receive path architecture for the transceiver chip of FIG. **4**A.

FIG. **5** is a flowchart of a method of constellation transformation according to one embodiment.

FIG. **6** is a schematic diagram of a first optical communication system in communication with another optical communication system via an optical network.

FIG. **7** is a plot of simulated bit-error-rate (BER) curves versus optical signal to noise ratio (OSNR).

FIG. **8** is a plot of one example of the measured average lane bit error rate (BER) versus offset of a vertical phase bias voltage.

FIGS. **9**A-**9**C show examples of constellation maps for vertical and horizontal polarizations for different phase bias voltage offsets.

DETAILED DESCRIPTION OF EMBODIMENTS

The following detailed description is directed to certain implementations for the purposes of describing the innovative aspects. However, the teachings herein can be applied in a multitude of different ways. As will be apparent from the following description, the innovative aspects may be implemented in any high-speed communication system that is configured to transmit and receive data between electronic devices which can include laptops, notebooks, tablets, desktop computers, data centers, gaming devices, data storage systems, input/output peripheral devices, display devices, etc. The innovative aspects may be implemented in or associated with data transport networks, storage area networks, enterprise networks, private networks, secure networks, financial networks, etc. Other uses are also possible.

A high-speed communication link can include an optical cable, such as a fiber-optic cable. Additionally, an optical transmitter positioned on one end of the optical cable can transmit data to an optical receiver positioned on the other end of the optical cable.

An optical transmitter can include optical modulators for transmitting optical signals over the optical cable. In certain implementations, the optical transmitter can employ automatic bias control to bias the optical modulators to enhance the accuracy of transmissions. In one example, an optical transmitter includes a first optical modulator for generating in-phase (I) optical signal, a second optical modulator for generating a quadrature-phase (Q) optical signal, and an automatic bias controller used to control biasing of the optical modulators. For instance, the automatic bias controller can generate a first bias voltage that controls an offset of the first optical modulator, a second bias voltage that controls an offset of the second optical modulator, and a third bias voltage that controls a phase difference between the I and Q optical signals.

Although automatic bias control can enhance the performance of communications over an optical cable, an automatic bias controller may not precisely control the bias voltages to the desired values. For example, the bias voltages can include small perturbations associated with dithering and/or the voltage levels of the bias voltages can drift due to a searching algorithm and/or a change in operating environment.

Errors in the optical transmitter's modulator bias voltages can lead to decoding errors at the optical receiver, such as burst errors and/or loss of frames. Sensitivity to errors in modulator biasing can be exacerbated in applications using high-order modulation formats, such as 16-QAM or discrete multitoned (DMT) modulation.

Apparatus and method for digital signal constellation transformation are provided herein. In certain configurations, an integrated circuit includes an analog front-end that converts an analog signal vector representing an optical signal into a digital signal vector, and a digital signal processing circuit that processes the digital signal vector to recover data from the optical signal. The digital signal processing circuit generates signal data representing a signal constellation of the digital signal vector. The digital signal processing circuit includes an adaptive gain equalizer that compensates the signal data for distortion of the signal constellation arising from biasing errors of optical modulators used to transmit the optical signal.

The teachings herein can be used to increase the tolerance of an optical receiver to modulator biasing errors, including bias errors that generate a phase error between I and Q components of the optical signal. For example, the optical receivers herein can exhibit enhanced robustness to biasing errors arising from dithering and/or a searching algorithm of an optical transmitter's automatic bias controller.

In certain implementations, the adaptive gain equalizer compensates the signal data for distortion based on detecting an amount of angular tilt of the signal constellation arising from modulator biasing errors. In one example, a QAM signal constellation ideally has about a 90° a separation between I and Q signal components, but modulator biasing errors can lead to the QAM signal constellation being at a tilted angle with respect to 90°. To compensate for the angular tilt, the adaptive gain equalizer can transform the signal data representing the signal constellation using a transformation matrix that includes an estimated value of the tilted angle.

In certain configurations, the estimated value of the titled angle is determined via iteration by adjusting a previous estimate of the titled angle based on a cross-correlation of I and Q components of the transformed signal data. In certain implementations, the estimated value of the titled angle is generated by iteratively adjusting the titled angle until the cross-correlation is within a convergence threshold. The cross-correlation can be implemented in a variety of ways, and can be performed over m data points of the signal constellation. In certain implementations, the m data points are associated with a sum of cross-correlations of a moving window of data samples. Thus, the estimated value of the titled angle can dynamically track changes to the modulator biasing errors. The iterative process can be controlled using a step gain K that can be adjusted to control a trade-off between convergence speed and stability. In certain implementations, the step gain K can be dynamically controlled, such as by changing the step gain K based on a number of times the titled angle has been iteratively estimated.

The integrated circuit can further include a decision slicer that slices the transformed signal data generated by the adaptive gain equalizer to determine where particular data points of the signal constellation belong. By compensating for distortion of the signal constellation before slicing, the bit error rate of an optical receiver can be reduced.

The teachings herein can be used to compensate for distortion of a signal constellation of a wide variety of formats, including, but not limited to, quadrature amplitude modulation (QAM), discrete multitoned (DMT) modulation, orthogonal frequency division multiplexing (OFDM), and phase-shift keying (PSK) (including, but not limited to, quadrature phase-shift keying (QPSK)) for both coherent and direct-detected systems. Although example signal formats have been provided, a digital signal constellation transformation can be applied to other signals, such as signals having a signal constellation that is substantially symmetric with respect to an origin.

Examples of Optical Communication Devices

FIG. **1** is a schematic diagram of one embodiment of an optical transceiver module or integrated optical module **108**. The optical transceiver module **108** includes a transceiver **110** and an optics block **111**. In the illustrated embodiment, the optics block **111** includes a transmit integrated tunable laser assembly (Tx iTLA) **112**, a receive integrated tunable laser assembly (Rx iTLA) **118**, an optical transmitter **114**, a driver **116**, and a coherent receiver **120**.

The optical transceiver module **108** receives transmit (Tx) data **124** from a host device on a host side, and processes the transmit data **124** to generate a transmit optical signal **130** for transmission over an optical cable on a line side. Additionally, the optical transceiver module **108** receives a receive (Rx) optical signal **132** from the optical cable, and processes the receive optical signal **132** to generate receive data **126** provided to the host device.

Although FIG. **1** illustrates one embodiment of an optical transceiver module, an optical transceiver module can be implemented in a wide variety of ways. For example, the optical transceiver module **108** of FIG. **1** can include more or fewer components and/or a different arrangement of components.

The optics block **111** can be implemented in a wide variety of ways. In one example, the optics block **111** is implemented to communicate over an optical cable based on Indium Phosphide (InP) modulator technology. In another example, the optics block **111** is implemented to communicate over an optical cable based on Lithium Niobate (LiNb) modulator technology. Although two examples of modulator technology have been provided, the teachings herein are applicable to a wide variety of modulator technologies.

In certain implementations, the transceiver **110** operates using a programmable host interface and/or programmable optical interface protocol, thereby enhancing flexibility by providing compatibility with a wide variety of host devices and/or optical networks. In one example, the transceiver **110** includes a host interface that can communicate using various standards such as, for example, 100 GE, OTU4, OTU3, and/or other interfacing standards. In another example, the transceiver **110** operates in conjunction with the optics block **111** to transmit and receive optical signals associated with a wide variety of optical communication protocols, including for example, QAM, DMT, and/or PSK (including, but not limited to, APSK and/or QPSK). The transceiver **110** can be implemented with internal mapping and framing capability to provide translation between the host interface protocol and the optical interface protocol. In certain implementations, the transceiver **110** has at least one of a programmable data rate or programmable error correction scheme.

The optical transceiver module **108** can communicate with a wide variety of host devices, including, but not limited to, a mobile computing device, a personal computing device, a workstation, a peripheral device, a hub, and/or a network router. In certain implementations, the transmit (Tx) data **124** and/or the receive (Rx) data **126** are digital electrical signals, such as multi-bit digital signals.

In the transmit direction of the optical transceiver module **108**, the transceiver **110** processes the transmit data **124** received from the host side to generate an analog transmit signal vector **192**. In one example, the analog transmit signal vector **192** includes four signals representing in-phase (I) and quadrature (Q) components for each of horizontal (H)

and vertical (V) polarizations (represented as HI, HQ, VI, and VQ in FIG. **1**). However, other implementations are possible.

In the receive direction of the optical transceiver module **108**, the transceiver **110** receives an analog receive signal vector **194** from the coherent receiver **120** and performs signal processing functions that can include, for example, equalization and/or timing recovery to generate the receive data **126**. In one example, the analog receive signal vector **194** includes four signals representing I and Q components for each of horizontal and vertical polarizations (represented as HI, HQ, VI, VQ in FIG. **1**). However, other implementations are possible.

In the optics block **111**, the Tx iTLA **112** generates an optical carrier signal and provides the optical carrier signal to the optical transmitter **114**. The driver **116** operates in combination with the optical transmitter **114** to modulate the HI/HQ and VI/VQ signals onto optical carriers in horizontal and vertical polarizations, respectively, for transmission over an optical cable on the line side. In the receive direction, the Rx iTLA **118** generates a local oscillator (LO) signal at approximately the carrier frequency of the received optical signal **132**. The coherent receiver **120** receives the LO signal from the Rx iTLA **118** and demodulates the incoming optical signal **132** to baseband to generate the analog receive signal vector **194**.

In one embodiment, the transceiver **110** generates an automatic gain control (AGC) signal **188**, which provides feedback to the coherent receiver **120** based on the strength of the analog receive signal vector **194**. The AGC signal **188** may comprise a single signal or multiple signals. In one example, the AGC signal **188** includes four gain control signals for controlling gain of HI, HQ, VI, and VQ signals of the analog receive signal vector **194**.

In certain implementations, the optical transceiver module **108** is implemented as a pluggable module that can be integrated in an optical communication system. Various features of the optical transceiver module **108** of FIG. **1** can be similar to those described in commonly-owned U.S. Pat. No. 9,071,364, issued Jun. 30, 2015, and titled "COHERENT OPTICAL TRANSCEIVER WITH PROGRAMMABLE APPLICATION MODES," which is herein incorporated by reference in its entirety for all purposes.

Although FIG. **1** illustrates one example of an optical communication device that can be implemented to provide a constellation transformation algorithm, the teachings herein are applicable to wide variety of optical communication devices. Moreover, although FIG. **1** illustrates a configuration including both a transmit path and a receive path, the teachings herein are also applicable to optical communication devices that omit a transmit path.

FIG. **2** is a schematic diagram of an optical transmitter **200** that can be employed to generate spectrally efficient optical signals. The optical transmitter **200** includes an optical splitter **202***a*, an optical coupler **202***b*, a horizontal I/Q optical modulating device **204**, a vertical I/Q optical modulating device **205**, an automatic bias controller **206**, a horizontal photodetector **210***a*, and a vertical photodetector **210***b*.

Although FIG. **2** illustrates one embodiment of an optical transmitter, an optical transmitter can be implemented in a wide variety of ways. For example, the optical transmitter **200** of FIG. **2** can include more or fewer components and/or a different arrangement of components.

The horizontal and vertical I/Q optical modulating devices **204** and **205** can be used to convert electrical I/Q signals into optical signals with orthogonal optical polarizations (for example, horizontal (H) and vertical (V) polarizations). In the illustrated embodiment, the horizontal and vertical I/Q optical modulating devices **204** and **205** each include a phase shifter and a pair of Mach-Zehnder modulators to convert electrical signals into I and Q optical signals or light waves. For example, the horizontal I/Q optical modulating device **204** includes a first optical modulator **204***a*, a second optical modulator **204***b*, and a phase shifter **208***a*. Additionally, the vertical I/Q optical modulating device **205** includes a first optical modulator **205***a*, a second optical modulator **205***b*, and a phase shifter **208***b*.

The optical transmitter **200** receives an input light beam along an input path **201***a*, and generates a modulated optical signal along an output path **201***b*. In one example, the input light beam corresponds to a light output from the Tx iTLA **112** of FIG. **1**, and the modulated optical signal corresponds to the Tx optical signal **130** of FIG. **1**. The input path **201***a* and the output path **201***b* can be implemented in a variety of ways, such as by using an optical waveguide and/or an optical fiber.

The optical splitter **202***a* splits the input light beam into a first component that is provided as an input to the horizontal I/Q optical modulating device **204** and a second component that is provided as an input to the vertical I/Q optical modulating device **205**. In the illustrated embodiment, the optical splitter **202***a* includes a polarization beam splitter (PBS) that can split the input light beam into a first component having horizontal (H) polarization (for example, TM polarization) and a second component having a vertical (V) polarization (for example, TE polarization). Although illustrated as a polarization beam splitter, the optical splitter **202***a* can be implemented in a wide variety of ways, such as by using waveguide and/or fiber-based optical components that split the optical power of the input light beam equally or unequally.

The first and the second components of the input light beam are coupled into input optical waveguides **215***a* and **217***a* of the horizontal and vertical I/Q optical modulating devices **204** and **205**, respectively. An optical splitter **203***a* further divides the first component of the input light between the optical modulators **204***a* and **204***b* of the horizontal I/Q optical modulating device **204**, and an optical splitter **203***c* divides the second component of the input light between the optical modulators **205***a* and **205***b* of the vertical I/Q optical modulating device **205**.

Light inputted into optical modulators **204***a*, **204***b*, **205***a*, and **205***b* is modulated with the electrical signals HI, HQ, VI and VQ, respectively. The light output of the optical modulators **204***b*, **205***b* is shifted using the phase shifters **208***a*, **208***b*, respectively. Additionally, the light outputs of the optical modulator **204***a* and the phase shifter **208***a* are combined using the optical coupler **203***b* and provided to an output waveguide **215***b*. Furthermore, the light outputs of the optical modulator **205***a* and the phase shifter **208***b* are combined using the optical coupler **203***d* and provided to an output waveguide **217***b*.

The optical splitters **203***a* and **203***c* and the optical couplers **203***b* and **203***d* can be implemented in a wide variety of ways, and can include directional couplers, multimode interference couplers and/or other optical components. As shown in FIG. **2**, modulated light propagating along the output optical waveguides **215***b* and **217***b* is combined by an optical coupler **202***b* to generate the modulated optical signal on the output path **201***b*. In the illustrated embodiment, the optical coupler **202***b* includes a polarization beam combiner. However, the optical coupler **202***b* can be imple-

mented in other ways, such as using optical waveguide and/or fiber-based components suitable for combining light beams.

The optical modulators **204***a*, **204***b*, **205***a* and **205***b* can be implemented in a wide variety of ways. In one example, the optical modulators **204***a*, **204***b*, **205***a* and **205***b* are Mach-Zehnder modulators implemented on a substrate including an electro-optic material such as, for example, lithium niobate ($LiNbO_3$) or indium phosphide (InP). For example, each of the Mach-Zehnder modulators can include an input waveguide that is split into a first branch and a second branch that extend along a length of the substrate and that are coupled together to form an output waveguide.

The illustrated optical transmitter **200** includes the automatic bias controller **206**, which generates bias voltages for biasing the horizontal and vertical I/Q optical modulating devices **204** and **205**. For example, with respect to the horizontal I/Q optical modulating device **204**, the automatic bias controller **206** generates a first bias voltage (BIAS HI) for biasing the first optical modulator **204***a*, a second bias voltage (BIAS HQ) for biasing the second optical modulator **204***b*, and a third bias voltage (BIAS HPD) for biasing the phase shifter **208***a*. Additionally, with respect to the vertical I/Q optical modulating device **205**, the automatic bias controller **206** generates a first bias voltage (BIAS VI) for biasing the first optical modulator **205***a*, a second bias voltage (BIAS VQ) for biasing the second optical modulator **205***b*, and a third bias voltage (BIAS VPD) for biasing the phase shifter **208***b*.

Although illustrated as part of the optical transmitter **200**, in certain implementations the automatic bias controller **206** is separate from the optical transmitter **200**. The automatic bias controller **206** can be implemented in a wide variety of ways, and can include one or more data converters, amplifiers, detectors, filters, microprocessors, microcontrollers, digital signal processors (DSPs), field programmable gate arrays (FPGAs), memories, and/or other electronic circuitry.

The automatic bias controller **206** controls the bias voltages of the horizontal I/Q optical modulating device **204** based on feedback received via the horizontal photodetector **210***a*. In one example, the automatic bias controller **206** controls a voltage level of the first bias voltage (BIAS HI) to control an offset of a horizontal I component of the modulated optical signal, controls a voltage level of the second bias voltage (BIAS HQ) to control an offset of a horizontal Q component of the modulated optical signal, and controls a voltage level of the third bias voltage (BIAS HPD) to control a phase difference between the horizontal I component and the horizontal Q component of the modulated optical signal to about 90 degrees. Similarly, the automatic bias controller **206** controls the bias voltages of the vertical I/Q optical modulating device **205** based on feedback received via the vertical photodetector **210***b*.

The bias voltages or points of the horizontal and vertical I/Q optical modulating devices **204** and **205** can change due to a wide variety of reasons, such as temperature changes, aging, and/or by dithering and/or a searching algorithm of the automatic bias controller **206**. In the illustrated embodiment, the automatic bias controller **206** receives feedback via the horizontal and vertical photodetectors **210***a*, **210***b*. However, other implementations of feedback can be used.

In one embodiment, the automatic bias controller **206** applies a low frequency dither signal to one or more of the bias points of the horizontal I/Q optical modulating device **204** and/or the vertical I/Q optical modulating device **205**. Additionally, the impact of the dithering can be observed via the horizontal and/or vertical photodetectors **210***a* and **210***b*. Thus, the automatic bias controller **206** can analyze and track the drifting of the biases by observing the impact of dithering. However, the automatic bias controller **206** can employ other tracking algorithms.

Although FIG. **2** illustrates one example of an optical transmitter that can be used to transmit a modulated optical signal, a constellation transformation algorithm can be applied to optical signals received from a wide variety of optical transmitters. For example, although FIG. **2** illustrates a configuration in which the modulated optical signal is a dual-polarization signal including both horizontal and vertical components, a constellation transformation algorithm can be applied to a received optical signal that includes a single polarization. Moreover, an optical receiver can provide a constellation transformation to an optical signal that is received from an optical transmitter that does not employ automatic bias control.

Examples of Compensating for Drift in Modulator Bias Voltages

The growth in global data traffic can lead to congestions in telecommunication networks. Such networks can benefit from using spectrally efficient modulation schemes including, for example, quadrature amplitude modulation (QAM) or discrete multitoned (DMT) modulation, which can accommodate more data channels within an available bandwidth with little to no increase in interference between channels.

However, the complexity of higher-order modulation formats can result in tighter margin and less tolerance to the impairment of optical transmission channels. For example, when operating near an error-correction threshold, a small perturbation or drifting of modulator bias voltages can cause a series of burst errors or even trigger loss of frames in the optical receiver. Sensitivity to bias voltage drift can be exacerbated in implementations using complex modulation formats, such as 16-QAM or DMT modulated signals.

An automatic bias controller, such as the automatic bias controller **206** of FIG. **2**, may efficiently compensate for drift of bias voltages used to control I and Q offset (for example, BIAS HI, BIAS HQ, BIAS VI, and BIAS VQ of FIG. **2**). However, the automatic bias controller may not fully compensate for the drift of the horizontal and/or vertical phase bias voltages (for example, BIAS HPD and BIAS VPD of FIG. **2**).

One reason for this can be that the strength of feedback associated with drift of the horizontal and/or vertical phase bias voltage (for example, BIAS HPD and BIAS VPD of FIG. **2**) can be significantly smaller, such as an order of magnitude smaller, than the strength of feedback associated with bias voltages used to control I and Q offset (for example, BIAS HI, BIAS HQ, BIAS VI, and BIAS VQ of FIG. **2**). Accordingly, an automatic bias controller may not accurately track drift of horizontal and/or vertical phase bias voltages, which can lead to bit-error rate (BER) fluctuations and/or burst errors for signals with complex modulation formats.

In an optical communication system, data from the received optical signal can be recovered using a coherent receiver (for example, the coherent receiver **120** of FIG. **1**), which in turn can be processed by a transceiver (for example the transceiver **110** FIG. **1**). The transceiver can perform one or more signal processing functions including, but not limited to, chromatic dispersion correction, timing recovery, carrier recovery, and/or feed-forward equalization (FFE) to compensate for signal distortions arising from loss and/or noise in the optical channel.

In one example, a transceiver recovers data from an optical signal in a 16-level quadrature amplitude modulated (QAM) format. In such an example, the recovered symbols of the 16-level QAM signal can be mapped onto a constellation diagram or map that includes 16 symbols in a two-dimensional X-Y plane scatter diagram. Additionally, each symbol represents 4-bits of digital data. Without any loss of generality, for a 16-QAM modulated optical signal, the X-axis of the constellation map can correspond to the I component and the Y-axis can correspond to the Q component of the recovered electrical signal, or vice versa.

However, errors in the optical transmitter's modulator bias voltages can lead to distortions in the constellation diagram, which can lead to errors in recovering symbols. For example, the bias voltages can include small perturbations associated with dithering and/or the voltage levels of the bias voltages can drift due to a searching algorithm and/or a change in operating environment.

Apparatus and method for digital signal constellation transformation are provided herein. In certain configurations, an integrated circuit includes an analog front-end that converts an analog signal vector representing an optical signal into a digital signal vector, and a digital signal processing circuit that processes the digital signal vector to recover data from the optical signal. The digital signal processing circuit generates signal data representing a signal constellation of the digital signal vector. The digital signal processing circuit includes an adaptive gain equalizer that compensates the signal data for distortion of the signal constellation arising from biasing errors of optical modulators used to transmit the optical signal.

In certain implementations, the adaptive gain equalizer compensates the signal data for distortion based on detecting an amount of angular tilt of the signal constellation arising from modulator biasing errors. In one example, a QAM signal constellation ideally has about a 90° a separation between I and Q signal components, but modulator biasing errors can lead to the QAM signal constellation being at a tilted angle with respect to 90°. To compensate for an angular tilt, the adaptive gain equalizer can transform the signal data representing the signal constellation using a transformation matrix that includes an estimated value of the tilted angle.

In certain configurations, the estimated value of the titled angle is determined via iteration by adjusting a previous estimate of the titled angle based on a cross-correlation of I and Q components of the transformed signal data. In certain implementations, the estimated value of the titled angle is generated by iteratively adjusting the titled angle until the cross-correlation is within a convergence threshold. The cross-correlation can be implemented in a variety of ways, and can be performed over m data points of the signal constellation. In certain implementations, the m data points are associated with a sum of the cross-correlation of a moving window of data samples. Thus, the estimated value of the titled angle can dynamically track changes to the modulator biasing errors. The iterative process can be controlled using a step gain K that can be adjusted to control a trade-off between convergence speed and stability. In certain implementations, the step gain K can be dynamically controlled, such as by changing the step gain K based on a number of times the titled angle has been iteratively estimated.

The integrated circuit can further include a decision slicer that slices the transformed signal data generated by the adaptive gain equalizer to determine where particular data points of the signal constellation belong. By compensating for distortion of the signal constellation before slicing, the bit error rate of an optical receiver can be reduced.

FIG. **3**A is a graph of two examples of constellation maps formed by the symbols of a 16-level QAM signal. The post-transformation constellation map **305** formed by dashed circles (for example, **305***a*, **305***b*) represents the location of the 16 symbols after application of one example of a constellation transformation algorithm in accordance with the teachings herein. Additionally, the pre-transformation constellation map **307** formed by solid circles (for example, **307***a*, **307***b*) represents the location of the 16 symbols prior to application of the constellation transformation algorithm.

As shown in FIG. **3**A, the pre-transformation constellation map **307** includes distortion associated with drift in horizontal and vertical phase bias voltages of horizontal and vertical I/Q optical modulating devices. Additionally, the post-transformation constellation map **305** has been compensated to reduce the impact of distortion arising from drift in the horizontal and vertical phase bias voltages.

As shown in FIG. **3**A, the 16 symbols of the post-transformation constellation map **305** are arranged along four rows and four columns that form a substantially rectangular grid parallel to the X- and Y-axes. However, the pre-transformation constellation map **307** illustrates that drift in the horizontal and/or vertical phase bias voltages can result in a constellation map being shifted, squeezed and/or rotated with respect to the X- and Y-axes.

For example, the pre-transformation constellation map **307** in FIG. **3**A is oriented at an angle θ with respect to an axis parallel to the Y-axis and at an angle ψ with respect to an axis parallel to the X-axis. In various embodiments, the angle θ can be equal to the angle ψ. In some embodiments, the angle θ can be greater than or less than the angle ψ. Various algorithms can be used to compensate for any differences in the magnitude of angle θ and angle ψ. For example, carrier recovery algorithms employed by carrier recovery blocks in receiver systems (e.g., transceiver **110**, transceiver chip **400**, receiver path architecture **450**, optical receiver **608***a* and **608***b*) can align the constellation to the diagonal axis centered at the origin such that the angle θ is approximately equal to the angle ψ. Examples of carrier recovery algorithms employed to compensate for any differences in the magnitude of angle θ and angle ψ can include coarse/fine carrier recovery, Viterbi-Viterbi estimation, etc.

In certain implementations, data recovered from an optical receive signal is provided to a slicer to determine the received symbol. For instance, with respect to the example shown in FIG. **3**A, a slicer can be used to determine which of the 16 symbols on the constellation diagram is closest to a received symbol, which may be degraded by noise, losses, and/or channel non-linearity. In additive white Gaussian noise (AWGN) channels, the slicer can determine the points by slicing about in the middle. For example, for the constellation maps **305** and **307** illustrated in FIG. **3**A, the decision boundary can be at [+0.5, 0, −0.5] for each axis. For instance, if a received symbol has an X-axis value less than −0.5 and a Y-axis value greater than +0.5, then the slicer may map the received symbol to symbol **305***a*.

As discussed above, errors in modulator biasing can distort a constellation. For example, drift of modulator phase bias voltages can result in the constellation being shifted, squeezed and/or rotated. For example, a constellation can be rotated or squeezed into a diamond shape, as depicted by the pre-transformation constellation map **307** of FIG. **3**A. As described herein, an integrated circuit can include an adap-

tive gain equalizer that compensates data representing a constellation map for errors in modulator bias voltages.

The distortion of the constellation map due to drift in horizontal and/or vertical bias voltages can result in a correlation between I and Q components of a constellation map. The distortion can lead to a decrease in extinction ratio or otherwise degrade performance.

The pre-transformation constellation map **307** in FIG. **3**A includes distortion resulting from a drift of a horizontal phase bias voltage of a horizontal I/Q optical modulating device **204** by an amount greater than 5 degrees, in this example. As discussed above, due to signal processing functions such as, for example, feed-forward equalization (FFE) and fine carrier recovery (FCR) performed by a digital signal processing circuit of a transceiver, the pre-transformation constellation map **307** is aligned at about a 45 degree diagonal line and centered at about the origin point such that the angle θ is approximately equal to the angle ψ. For example, in various embodiments, the difference between angle θ and the angle can be less than 10%. The constellation distortion can be viewed as a two-dimensional (2D) axis transformation.

The teachings herein can be used to compensate for drift in horizontal and/or vertical phase bias voltages of optical modulating devices. In certain configurations, a digital signal processing circuit processes received data using a constellation transformation algorithm (CTA).

In one embodiment, the constellation transformation algorithm compensates for an angular tilt of a constellation map, such as the pre-transformation constellation map **307** of FIG. **3**A, by applying a transformation matrix given by equation (1) below. By compensating the constellation map for distortion before slicing, the bit error rate of an optical receiver can be reduced.

$$\frac{1}{\cos^2\theta-\sin^2\theta}\begin{bmatrix}\cos\theta & -\sin\theta\\ -\sin\theta & \cos\theta\end{bmatrix} \quad (1)$$

In equation (1) above, θ represents the tilt of the constellation map from an ideal position, such as an orthogonal position. In one embodiment, θ is obtained iteratively using equation (2) below, where wi and wq are I and Q components, respectively, of a recovered optical signal after feed-forward equalization (FFE) and carrier recovery.

$$\theta_n=\theta_{n-1}+R(wi,wq)\times K \quad (2)$$

In equation (2) above equation, K is the step gain factor, which can be adjusted to increase convergence speed and/or stability. The step gain factor K can be selected based on the noise in the channel. Additionally, R(wi, wq) is the cross-correlation function of wi, wq. In one embodiment, R(wi, wq) is given by equation (3) below, where m is the number of data points used in the cross-correlation function.

$$R(w_i,w_q)=\Sigma_m w_i[m]\times w_q[m] \quad (2)$$

In one embodiment, at each n^{th} iteration, the integrated circuit implementing the algorithm: (1) generates a new transformation matrix M_n based on the value of θ_n obtained in the n^{th} iteration in equation (1) above; (2) applies the new transformation matrix M_n to the constellation map C_{n-1} obtained in the $(n-1)^{th}$ iteration to obtain a new constellation map C_n; (3) derives modified I and Q components wi_n and wq_n from the new constellation map C_n; and (4) determines the cross-correlation between the derived modified I and Q components wi_n and wq_n.

In certain implementations, the algorithm is converged to the point where $R(wi_n, wq_n)$ is close to zero(0), such as when $R(wi_n, wq_n)$ is less than a convergence threshold. For example, convergence can be considered to be achieved if $R(wi_n, wq_n)$ is less than or equal to a threshold value (for example, less than or equal to 0.5, less than or equal to 0.1, less than or equal to 0.01, less than or equal to 0.001, less than or equal to 0.0001 or values in between these ranges and sub-ranges). Converging the algorithm in this manner can be used to determine when the I and Q signals are substantially uncorrelated. In one embodiment, the algorithm is converged until the I and Q signals are substantially orthogonal. In certain implementations, the step gain factor K can be adaptively controlled. For example, the step gain factor K can be adaptively changed over time such that it is relatively large in the beginning of the iterative process and is relatively small as $R(wi_n, wq_n)$ approaches zero(0).

In one embodiment, the integrated circuit implementing the algorithm provides a constellation transformation separately to I/Q data associated with horizontal and vertical polarizations. Implementing the integrated circuit in this manner enhances the accuracy of constellation transformation by allowing different amounts of tilt adjustment to be provided for a horizontal constellation map and for a vertical constellation map. In such an embodiment, θ_H for adjusting a horizontal constellation map is obtained by iteratively processing I and Q data associated with a horizontal polarization, and θ_V for adjusting a vertical constellation map is obtained by iteratively processing I and Q data associated with a vertical polarization. In one embodiment, the digital signal vector includes data representing a single polarization modulation or a dual-polarization modulation, and the integrated circuit is configurable between a first mode in which a tilt adjustment is provided to the data representing the single polarization modulation, and a second mode in which a separate tilt adjustment for each polarization is provided to the data representing the dual-polarization modulation. Thus, in one embodiment, an IC can be configurable to selectively process a signal of single polarization modulation or a signal of dual-polarization modulation. In another embodiment, an IC is operable to process signals of single polarization modulation but not of dual polarization modulation. In yet another embodiment, an IC is operable to process signals of dual-polarization modulation but not of single polarization modulation.

FIGS. **3**B and **3**C are two examples of plots illustrating convergence of tilt angle as a function of the number of iterations for different signal-to-noise ratio (SNR) levels. FIG. **3**B illustrates convergence for a 30 dB SNR level, and FIG. **3**C illustrates convergence for a 10 dB SNR level.

In the illustrated examples, SNR is calculated based on constellations in an AWGN channel. Additionally, after the first 250 iterations, step gain factor K is reduced by factor of 5 to improve stability. Because the data baud rate can be significantly higher than drifting associated with an automatic bias controller, the tracking algorithm can exhibit robustness to variation in SNR. For example, when the SNR level increases, the number of data points m used in the cross-correlation function can be increased to average out the noise.

Example Transceiver Chip

FIG. **4**A is a schematic diagram of an optical transceiver system **430** according to one embodiment. The optical transceiver system **430** includes a transceiver chip or integrated circuit (IC) **400**, a coherent optical receiver **404**, an optical transmitter **422**, a receive laser **414**, and a transmit laser **418**.

Although FIG. **4**A illustrates one embodiment of an optical transceiver system, an optical transceiver system can be implemented in a wide variety of ways. For example, the optical transceiver system **430** of FIG. **4**A can include more or fewer components and/or a different arrangement of components. Additionally, although illustrated in the context of an optical transceiver system, a constellation transformation algorithm can be employed in an optical communication system that omits a transmit path.

As shown in FIG. **4**A, the coherent optical receiver **404** generates an analog receive signal vector **408** based on a received optical signal **406** from an optical cable on a line side. The transceiver chip **400** processes the analog receive signal vector **408** to generate receive data **403** for a host device on a host side. As shown in FIG. **4**A, the coherent optical receiver **404** receives a local oscillator signal from the receive laser **414**, which can be, for example, a continuous wave (CW) laser or integrated tunable laser assembly. The transceiver chip **400** also processes transmit data **402** received form the host side to generate an analog transmit signal vector **420** for the optical transmitter **422**. The optical transmitter **422** modulates the analog transmit signal vector **420** using an optical carrier signal from the transmit laser **418** to generate an optical transmit signal **424**. Additional details can be similar to those described earlier.

The illustrated transceiver chip **400** includes an analog front-end **410** and a digital processing circuit **412** that includes an adaptive gain equalizer (AGE) **416**. The transceiver chip **400** is implemented to provide a constellation transformation algorithm to compensate for distortion in a constellation map recovered from the received optical signal **406**.

In the illustrated embodiment, the analog front-end **410** receives the analog receive signal vector **408**, which includes HI, HQ, VI, VQ signals in this example. Additionally, the analog front-end **410** processes the analog receive signal vector **408** to generate a digital receive signal vector **409** that is provided to the digital processing circuit **412**.

The digital signal processing circuit **412** can provide a wide variety of processing to the digital receive signal vector **409**, including, for example, skew correction, filtering, clock recovery, decoding, I and Q amplitude imbalance correction, I and Q phase imbalance correction, compensation for phase noise of the optical carrier, chromatic dispersion compensation, and/or intersymbol interference (ISI) correction. The digital signal processing circuit **412** also generates data representing an original constellation map associated with I and Q signal components recovered from the received optical signal **406**.

The digital signal processing circuit **412** also includes the AGE **416**, which implements a constellation transformation algorithm. The AGE **416** can implement the constellation transformation algorithm on the data representing the original constellation map, prior to decision slicing and demapping. As described earlier, the AGE **416** can perform a cross-correlation of I and Q components of the data representing the original constellation map, and determine an initial estimate of the tilt angle of the original constellation map. When distortion of the original constellation map is present, the AGE **416** can revise the estimate of the tilt angle θ of the original constellation map by an iterative process, as was described earlier. The AGE **416** can terminate the iterative process once the cross-correlation between the I and Q components is below a threshold value. The AGE **416** can further output a transformed constellation map that is compensated for tilt resulting from a drift in horizontal and/or vertical phase bias voltage. In certain implementations, the AGE **416** applies a transformation matrix given in equation (1) above to the original constellation map.

Additional details of the optical transceiver system **430** of FIG. **4**A can be similar to those described earlier.

FIG. **4**B is a schematic diagram of one embodiment of a transmit path architecture **440** for the transceiver chip **400** of FIG. **4**A. The transmit path architecture **440** receives data from a host device and processes the data to generate an analog transmit signal vector for an optical transmitter.

The illustrated transmit path architecture **440** includes an egress host interface **4102**, an egress framer/mapper **4104**, a forward error correction (FEC) encoder **4106**, a differential encoder and constellation mapper **4108**, a gear box **4109**, a digital signal processing core **4110**, an interpolator **4112**, a FIFO **4114**, and a transmit analog front-end (AFE) **4120**. As shown in FIG. **4**B, the differential encoder and constellation mapper **4108** includes a horizontal encoder and constellation mapper **4108**-*a* and a vertical encoder and constellation mapper **4108**-*b*. Additionally, the digital signal processing core **4110** includes a spectral shaping and preemphasis filter **4111**, and the transmit AFE **4120** includes a skew compensation block **4122** and a digital-to-analog converter (DAC) block **4126**.

The egress host interface **4102** processes received data signals from a host device. In certain implementations, the egress host interface **4102** also includes a host demultiplexer configured to recover clock signals from, and demultiplex, the received data signals. The egress host interface **4102** may also perform various processing functions such as, for example, equalization, signal integrity monitoring, and/or skew compensation. The egress framer/mapper **4104** is configured to receive data from the egress host interface **4102** and perform framing/mapping of the data according to a programmable framing/mapping protocol. The FEC encoder **4106** can add error correction bytes according to a forward error correction scheme suitable for a particular optical network. In this example, the differential encoder and constellation mapper **4108** receives four input signal data streams (for example, HI, HQ, VI, and VQ) and generates output signals using dual-polarization (DP) differential or non-differential modulation formats, including, for example, PSK, BPSK, QPSK, 16QAM, and/or QAM of other indices or levels. In certain implementations, processing is performed on a per-polarization basis (for example, separately for each of the horizontal and vertical polarizations using encoders/mappers **4108**-*a* and **4108**-*b*, respectively), or using an encoding/mapping procedure that mixes polarizations.

The gear box **4109** can receive the signal stream from the differential encoder and constellation mapper **4108** at a net data rate corresponding to a nominal data rate and reformat the data in the signal stream to a new data rate to accommodate any modifications to FEC code words. Additionally, the gear box **4109** generates an output signal stream including data at the nominal data rate (for example, at the same data rate as that of the input stream to the gear box **4109**). Accordingly, the gear box **4109** is operable to change the parallelization factor of the egress path. In the illustrated embodiment, the digital signal processing core **4110** includes a spectral shaping and preemphasis filter for each lane HI, HQ, VI and VQ. The spectral shaping and preemphasis filter **4111** can be designed to have a frequency response that pre-compensates for, or pre-equalizes, frequency-dependent attenuation of the electrical path between the DAC and the optical transmitter. The interpolator **4112** interpolates the data signal from the digital signal processing core **4110** to convert between sampling rates to enable

different components of the egress path architecture to operate at different sampling rates.

The FIFO **4114** includes a data storage buffer that stores and queues blocks of data received in parallel from the interpolator **4112**. The FIFO **4114** feeds the data to the transmit AFE **4120**. The transmit AFE **4120** includes the skew compensation filter **4122**, which compensates the data for skew introduced by the optical transmitter and the electrical signal path associated with the signal lanes of the DAC block **4126**. The DAC block **4126** receives the skew-compensated data, and generates analog signals (HI, HQ, VI, VQ) for transmission to the optical transmitter.

The transmit path architecture **440** of FIG. **4**B illustrates one example of transmit path circuitry suitable for a transceiver chip. However, a transceiver chip can include transmit path architectures implemented in a wide variety of ways.

FIG. **4**C is a schematic diagram of one embodiment of a receive path architecture **450** for the transceiver chip of FIG. **4**A. The receive path architecture **450** receives an analog receive signal vector from an optical receiver and processes the data to generate transmit data for a host device.

The illustrated receive path architecture **450** includes a receive analog front-end (AFE) **4148**, a digital signal processing circuit **4155**, a decision demapper or slicer **4176**, a gear box **4177**, an ingress framer/demapper **4178**, a FEC decoder **4180**, and an ingress host interface **4182**.

The illustrated receive AFE **4148** includes an analog-to-digital converter (ADC) block **4152** that converts the analog receive signal vector to a digital signal vector, which is processed by skew compensation filters **4154** to compensate for differences in signal delays. The ADC block **4152** can be programmable to operate with different resolutions and/or different programmable data rates (for example, 32 GSa/s for DP-16QAM, 64 GSa/s for DP-QPSK, at 128 Gb/s line rate). In certain implementations, the receive AFE **4148** can include a line demultiplexer configured to parallelize the data for processing by the digital signal processing circuit **4155**. In the illustrated embodiment, the receive AFE **4148** also includes an automatic gain control circuit **4153** that detects the amplitude of the received analog signals and provides feedback to the optical receiver to control gain.

The illustrated digital signal processing circuit **4155** includes a generic matrix rotator **4156**, a bulk chromatic dispersion (BCD) equalizer **4158**, a fiber length estimator **4160**, a coarse carrier recovery block **4162**, a FIFO **4163**, an interpolator **4164**, a timing recovery block **4166**, a feed-forward equalizer (FFE) **4170**, a feedback fine carrier recovery block **4172**, a feedforward fine carrier recovery block **4174**, and an AGE **416**.

The generic matrix rotator **4156** applies a matrix transformation to the digital signal vector to compensate for impairments associated with optical demodulation in the optical receiver. Additionally, the BCD equalizer **4158** includes a horizontal compensator/equalizer **4158**-*a* and a vertical compensator/equalizer **4158**-*b*, which operate to compensate for chromatic dispersion in the optical channel. Furthermore, the fiber length estimator **4160** can estimate the extent or amount of chromatic dispersion introduced by the optical channel to select a mode of operation of the BCD equalizer **4158**, and the coarse carrier recovery block **4162** performs an initial frequency acquisition or carrier recovery of the received signal during a start-up phase.

The FIFO **4163** operates as a data storage buffer that stores and queues blocks of data samples received from the BCD equalizer **4158**. The interpolator **4164** processes data from the FIFO **4163** to correct for I/Q imbalances, such as skew between I and Q components and/or a difference in amplitude between I and Q components. The interpolator **4164** can perform sampling rate conversion to interface between the digital signal processing circuit **4155** and the receive AFE **4148** without loss of data samples. The timing recovery block **4166** estimates the frequency and phase of the received data signal and generates timing information used to recover the data. The FFE **4170** filters the data and applies equalization to compensate for intersymbol interference (ISI) effects imposed by the optical and electrical channels. The feedback fine carrier recovery block **4172** and the feedforward fine carrier recovery block **4174** further refine the carrier recovery performed by the coarse carrier recovery block **4162**. As shown in FIG. **4**C, the feedback fine carrier recovery block **4172** provides a feedback signal FBK to the generic matrix rotator **4156**.

The AGE **416** processes I and Q data from the feedforward fine recover block **4174**. The AGE **416** provides a constellation transformation algorithm, which can be as described earlier. In the illustrated embodiment, the AGE **416** provides constellation transformation to digital I and Q data after feed-forward equalization (FFE) and carrier recovery.

In one embodiment, the AGE **416** provides a constellation transformation separately to I/Q data associated with horizontal and vertical polarizations. Implementing the AGE **416** in this manner enhances the accuracy of constellation transformation by allowing different amounts of tilt adjustment to be provided for a horizontal constellation map and for a vertical constellation map.

The decision demapper or slicer **4176** operates to decode transformed constellation data from the AGE **416**. The decision demapper or slicer **4176** can provide a variety of information, such as the most probable decoded bits based on the transformed constellation data. The gear box **4177** can change a parallelization factor of the data from the decision demapper **4176**. The ingress framer/demapper **4178** performs framing and demapping of data so as to transform modulation symbols to source bits. The FEC decoder **4180** can be used to add error correction using a forward error correct scheme. The ingress host interface **4182** is used to provide data to a host device using a desired protocol. In certain implementations, the ingress host interface **4182** includes a host multiplexer for multiplexing data provided to the host device.

The receive path architecture **450** of FIG. **4**C illustrates one example of receive circuitry suitable for a transceiver chip. However, a transceiver chip can include receive path architectures implemented in a wide variety of ways.

Example Method of Transforming Constellation Map to Compensate for Tilt

FIG. **5** is a flowchart of a method **500** of constellation transformation according to one embodiment.

The method **500** includes receiving an optical signal as depicted in block **502**. The optical signal can be similar to the received optical signal **132** discussed above with reference to FIG. **1** and/or the received optical signal **406** discussed above with reference to FIG. **4**A. The optical signal can be received by a coherent receiver (for example, coherent receiver **120** and/or coherent receiver **404**).

As shown in block **504**, I and Q components are recovered from the received optical signal. The I and Q components can recovered and processed as discussed above to compensate for various channel and optical demodulator impairments. For example, the recovered I and Q components can be obtained by converting the electrical signals received from the coherent optical receiver into digital format and

processing the digital signal using a digital signal processing circuit (for example, the digital signal processing circuit **412**), which can include the one or more of various functional blocks described earlier. In certain implementations, the I and Q components are processed for at least one of feed-forward equalization (FFE) or carrier recovery.

An initial constellation map $C_{initial}$ can be generated based on the recovered I and Q components as shown in block **506**. Additionally, as shown in block **508**, an initial angular tilt $\theta_{initial}$ of the initial constellation map $C_{initial}$ is estimated. In certain implementations, the tilt angle is measured with respect to an orthogonal constellation map.

As shown in block **510**, the tilt angle is iteratively adjusted based on a cross-correlation between I and Q components derived from intermediate transformed constellation maps obtained during the iterative process. For example, the iterative process can be used to obtain a new transformation matrix M_n obtained by substituting the value of θ_n obtained at each n^{th} iteration of the iterative process in equation (1) above. Additionally, the new transformation matrix M_n can be applied to the constellation map C_{n-1} obtained in the $(n-1)^{th}$ iteration of the iterative process to obtain a new constellation map C. Furthermore, modified I and Q components wi_n and wq_n can be derived from the new constellation map C_n, and the cross-correlation between the derived I and Q components wi_n and wq_n can be processed to revise the estimate of the angular tilt.

The iterative process can be terminated when the cross-correlation between I and Q components derived from transformed constellation map obtained during the n^{th} iteration of the iterative process $R(wi_n, wq_n)$ is about zero (0). For example, the iterative process can be terminated if $R(wi_n, wq_n)$ is less than or equal to a convergence threshold value (for example, less than or equal to 0.5, less than or equal to 0.1, less than or equal to 0.01, less than or equal to 0.001, less than or equal to 0.0001 or values in between these ranges and sub-ranges). The tilt angle $\theta_{converged}$ obtained at the end of the iterative of the iterative process can be considered to be the converged estimate of the tilt of the initial constellation map $C_{initial}$ relative to the selected angular reference point.

At the end of the iterative process, a transformed constellation map is obtained as shown in block **514**. The transformed constellation map can be equivalent to the constellation map obtained by applying a transformation matrix M calculated by substituting the tilt angle $\theta_{converged}$ to the initial constellation map $C_{initial}$. The transformed constellation map is provided to the decision slicer, as shown in block **514**, to decode the recovered I and the Q components for further processing. The method **500** can be implemented using an electronic hardware processor such as for example the transceiver **110**, the transceiver chip **400**, the digital signal processing circuit **412**, the optical receivers **608***a* and/or **608***b* described herein.

In one embodiment, the method **500** of FIG. **5** is performed with respect to I/Q components obtained from an optical signal including a single polarization. In another embodiment, the method **500** is performed with respect to two sets of I/Q components obtained from an optical signal including dual-polarization. For example, a first constellation transformation can be performed on a first set of I/Q data associated with a horizontal polarization, and a second constellation transformation can be performed on a second set of I/Q data associated with a vertical polarization. Thus, different amounts of tilt adjustment can be provided for a horizontal constellation map and for a vertical constellation map. In such an embodiment, θ_H for adjusting a horizontal constellation map is obtained by iteratively processing the first set of I/Q data associated with horizontal polarization, and θ_V for adjusting a vertical constellation map is obtained by iteratively processing I/Q data associated with a vertical polarization.

Additional details of the method **500** can be as described earlier.

Example Optical Communication Systems

FIG. **6** is a schematic diagram **600** of an optical communication system **604***a* in communication with another optical communication system **604***b* via an optical network **602**.

The optical communication system **604***a* includes an optical transmitter **606***a*, an optical receiver **608***a*, and an AGE **610***a* configured to implement a constellation transformation algorithm to compensate for the tilt in a constellation map of a received signal as a result of bias drifts. The optical communication system **604***b* includes an optical transmitter **606***b*, an optical receiver **608***b*, and an AGE **610***b* configured to implement a constellation transformation algorithm to compensate for the tilt in a constellation map of a received signal as a result of bias drifts.

The optical communication systems **604***a* and **604***b* can operate in a router, a server, a hub, a datacenter system, a network backhaul system, a computer, a phone system, or any other system that transmits and receives optical signals over the optical network **602**. The optical network **602** can be a DWDM network, an OFDM network, a TDM network, etc. In various implementations, the optical communication systems **606***a* and **606***b* can include one or more components and functional blocks similar to one or more of the components and functional blocks of the transceiver architecture described above with reference to FIGS. **4**A-**4**C.

Example Experimental Results

FIG. **7** is a plot of simulated bit-error-rate (BER) curves versus optical signal to noise ratio (OSNR) for optical signals generated by modulators in which one of the horizontal phase bias voltage or the vertical phase bias voltage had a drift of 2, 5 and 10-degrees. The BER curves are obtained by simulating constellations associated with a 16-level Quadrature amplitude modulated (QAM) signal.

Curves **702**, **704** and **706** represent the simulated BER curves when the horizontal or the vertical phase bias voltage drift is 2, 5 and 10-degrees respectively. It is noted that the power penalty at a BER of 10^{-3} is about 2 dB for a 5-degree offset in bias. A 5-degree offset for a $LiNbO_3$ modulator translates to about 200 mV of fluctuation in the bias voltage when biased around a null point of about 4V. Thus, small fluctuations in the bias voltage can result in significant decrease in link power budget. Curves **708**, **710** and **712** represent the simulated BER curves the constellation map is transformed by one implementation of a constellation transformation algorithm to compensate for horizontal or the vertical phase bias voltage offset of 2, 5 and 10-degrees respectively. It is noted that the OSNR specification to obtain a BER of 10^{-3} does not change when the constellation map is transformed to compensate for the bias offsets.

To further test the robustness and effectiveness of the constellation transformation algorithm, experiments were conducted with an integrated System-on-Chip (SoC) solution, which included analog front-ends (ADC and DAC), appropriate digital signal processing blocks, and signal generators and bit-error-rate testers. The setup and/or architecture of the SoC solution can be similar to the system and architecture depicted in FIG. **4**A. For testing purposes a 253.27-Gb/s dual-polarization (DP) 16-QAM optical signals were generated via Fujitsu DP-QPSK Mach-Zehnder Modulator (MZM). Eight (8) channels with different pseudo

random bits sequence (PRBS) were mapped onto the two 16-QAM constellations and sent through four on-chip DACs at 31.66-GBaud each. On the receiver side, four on-chip ADCs were used to sample the signals from an integrated coherent receiver and eight (8) corresponding channel BER tester (BERT) was used to compute BER simultaneously after the digital signal processing blocks. The signals measured by the BERT were not compensated for the offsets in the bias voltage.

An on-chip diagnostic unit was used to capture the demodulated constellation after the digital signal processing block and input into a computer for post processing which included transforming the constellation map to compensate for the bias offset. Although the system was configured as dual-polarization system, an offset was introduced in only the vertical phase bias voltage and BER was monitored. The BER of optical signals with horizontal-polarization were substantially unaffected since digital signal processing block could isolate the two polarizations using constant modulus algorithm (CMA).

FIG. **8** is a plot of the measured average lane BER versus offset in the vertical phase bias voltage. The average lane BER can be obtained by averaging the BER obtained for I and Q components. Curve **802** of FIG. **8** illustrates the measured average lane BER obtained by post-processing the de-modulated constellation using one implementation of a constellation transformation algorithm (CTA) to compensate for the offset in the vertical phase bias voltage and curve **804** obtained without transforming the constellation map to compensate for the offset in the vertical phase bias voltage. It is noted that the uncompensated BER curve **804** shows an increase in BER as the offset in the vertical phase bias voltage increases indicating degradation of the quality of the recovered signals. It is also noted that the compensated BER curve **802** shows relatively constant BER as the offset in the vertical phase bias voltage increases indicating that the quality of the recovered signals is maintained.

FIG. **9**A illustrates the constellation maps for the vertical and horizontal polarizations when the offset in the vertical phase bias voltage was 0.1V. In FIG. **9**A, constellation map **901***a* depicts the in-phase (I) and quadrature-phase (Q) components recovered from the optical signal with vertical polarization signal and constellation map **901***b* depicts I and Q components recovered from the optical signal with horizontal polarization.

FIG. **9**B illustrates the constellation maps for the vertical and horizontal polarizations when the offset in the vertical phase bias voltage is 0.3V. In FIG. **9**B, constellation map **903***a* depicts the in-phase (I) and quadrature-phase (Q) components recovered from the optical signal with vertical polarization signal and constellation map **903***b* depicts the in-phase (I) and quadrature-phase (Q) components recovered from the optical signal with horizontal polarization.

FIG. **9**C illustrates the constellation maps for the vertical and horizontal polarizations when the offset in the vertical phase bias voltage was −0.5V. In FIG. **9**C, constellation map **905***a* depicts the I and Q components recovered from the optical signal with vertical polarization signal and constellation map **905***b* depicts the I and Q components recovered from the optical signal with horizontal polarization.

The constellation maps illustrated in FIGS. **9**A, **9**B and **9**C depict the constellation map prior to transformation to correct for the offset in the vertical phase bias voltage. The post-processing constellation transformation algorithm discussed herein can be used to compensate for the tilt of the depicted maps with respect to orthogonal axes. Although the constellation maps of FIGS. **9**A, **9**B and **9**C illustrated various examples of constellations that can be compensated, the teachings herein can be used to provide compensation to a wide variety of signal constellations.

CONCLUSION

Unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise," "comprising," and the like are to be construed in an inclusive sense, as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to." The word "coupled", as generally used herein, refers to two or more elements that may be either directly connected, or connected by way of one or more intermediate elements. Additionally, the word "connected", as generally used herein, refers to two or more elements that may be either directly connected, or connected by way of one or more intermediate elements. Additionally, the words "herein," "above," "below," and words of similar import, when used in this application, shall refer to this application as a whole and not to any particular portions of this application. Where the context permits, words in the above Detailed Description using the singular or plural number may also include the plural or singular number respectively. The word "or" in reference to a list of two or more items, that word covers all of the following interpretations of the word: any of the items in the list, all of the items in the list, and any combination of the items in the list.

Moreover, conditional language used herein, such as, among others, "can," "could," "might," "can," "e.g.," "for example," "such as" and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements and/or states. Thus, such conditional language is not generally intended to imply that features, elements and/or states are in any way required for one or more embodiments or that one or more embodiments necessarily include logic for deciding, with or without author input or prompting, whether these features, elements and/or states are included or are to be performed in any particular embodiment.

The above detailed description of embodiments of the invention is not intended to be exhaustive or to limit the invention to the precise form disclosed above. While specific embodiments of, and examples for, the invention are described above for illustrative purposes, various equivalent modifications are possible within the scope of the invention, as those skilled in the relevant art will recognize. For example, while processes or blocks are presented in a given order, alternative embodiments may perform routines having steps, or employ systems having blocks, in a different order, and some processes or blocks may be deleted, moved, added, subdivided, combined, and/or modified. Each of these processes or blocks may be implemented in a variety of different ways. Also, while processes or blocks are at times shown as being performed in series, these processes or blocks may instead be performed in parallel, or may be performed at different times.

The teachings of the invention provided herein can be applied to other systems, not necessarily the system described above. The elements and acts of the various embodiments described above can be combined to provide further embodiments.

While certain embodiments of the inventions have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of

the disclosure. Indeed, the novel methods and systems described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the methods and systems described herein may be made without departing from the spirit of the disclosure. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the disclosure.

What is claimed is:

1. A method of operating an integrated optical module, the method comprising:

receiving, by a coherent optical receiver, an optical signal from an optical cable of the integrated optical module;

generating, by the coherent optical receiver, an analog signal representing the optical signal;

processing, by a transceiver, the analog vector to generate a digital signal vector, wherein the digital signal vector comprises a digital representation of an in-phase (I) component and a quadrature-phase (Q) component of the optical signal; and

generating, by the transceiver, signal data representing a signal constellation of the digital signal vector;

wherein generating the signal data comprises

generating, by an adaptive gain equalizer of the transceiver, transformed signal data by compensating the signal data for distortion of the signal constellation,

generating, by the adaptive gain equalizer, an estimate of an angular tilt of the signal constellation, and

compensating, by the adaptive gain equalizer, the signal data based on the estimate of the angular tilt.

2. The method of claim **1** wherein generating the estimate of the angular tilt comprises generating, by the adaptive gain equalizer, the angular tilt based on a sum of a plurality of cross-correlations of I and Q components of the signal constellation.

3. The method of claim **2** wherein the sum of the plurality of cross-correlations is computed over a moving window of data samples obtained from the digital signal vector.

4. The method of claim **1** wherein generating the estimate of the angular tilt further comprises iteratively revising, by the adaptive gain equalizer, the estimate of the angular tilt until I and Q components of the transformed signal data are substantially uncorrelated.

5. The method of claim **4** wherein iteratively revising the estimate of the angular tilt comprises iteratively revising, by the adaptive gain equalizer, the estimate of the angular tilt based on a step gain, wherein the step gain changes based on a number of times the angular tilt has been estimated.

6. The method of claim **1** wherein generating the transformed signal data comprises generating, by the adaptive gain equalizer, the transformed signal data based on a transformation matrix that includes the estimate of the angular tilt.

7. The method of claim **6** wherein the transformation matrix is about equal to

$$\frac{1}{\cos^2\theta-\sin^2\theta}\begin{bmatrix}\cos\theta & -\sin\theta\\ -\sin\theta & \cos\theta\end{bmatrix},$$

wherein θ is the estimate of the angular tilt.

8. The method of claim **1** further comprising processing, by the digital signal processing circuit, the signal data for at least one of feed forward equalization or carrier recovery prior to compensating the signal data for distortion of the signal constellation.

9. The method of claim **1** further comprising slicing, by a decision slicer, the transformed signal data.

10. The method of claim **1** wherein the distortion of the signal constellation comprises at least one of squeezing, shifting, or tilting.

11. The method of claim **1** wherein the optical signal comprises a multi-level quadrature amplitude modulation (QAM) signal, a discrete multi-toned (DMT) modulation signal, an orthogonal frequency division multiplexing (OFDM), or a phase-shift keying (PSK) signal.

12. The method of claim **1** wherein the digital signal vector comprises data representing a single polarization modulation or a dual-polarization modulation.

13. A method of operating an integrated optical module, the method comprising:

receiving, by a coherent optical receiver, an optical signal from an optical cable of the integrated optical module;

generating, by the coherent optical receiver, an analog signal vector representing the optical signal;

processing, by a transceiver, the analog signal vector to generate a digital signal vector, wherein the digital signal vector comprises a digital representation of an in-phase (I) component and a quadrature-phase (Q) component of the optical signal; and

generating, by the transceiver, signal data representing a signal constellation of the digital signal vector;

wherein generating the signal data comprises

generating, by an adaptive gain equalizer of the transceiver, transformed signal data by compensating the signal data for distortion of the signal constellation,

compensating, by the adaptive gain equalizer, for distortion for a first portion of the signal data associated with a horizontal polarization of the optical signal, and

compensating, by the adaptive gain equalizer, for distortion for a second portion of the signal data associated with a vertical polarization of the optical signal.

14. The method of claim **13** wherein generating the transformed signal data comprises generating, by the adaptive gain equalizer, the transformed signal data based on a transformation matrix that includes the estimate of the angular tilt.

15. The method of claim **14** wherein the transformation matrix is about equal to

$$\frac{1}{\cos^2\theta-\sin^2\theta}\begin{bmatrix}\cos\theta & -\sin\theta\\ -\sin\theta & \cos\theta\end{bmatrix},$$

wherein θ is the estimate of the angular tilt.

16. The method of claim **13** further comprising processing, by the digital signal processing circuit, the signal data for at least one of feed forward equalization or carrier recovery prior to compensating the signal data for distortion of the signal constellation.

17. The method of claim **13** further comprising slicing, by a decision slicer, the transformed signal data.

18. The method of claim **13** wherein the distortion of the signal constellation comprises at least one of squeezing, shifting, or tilting.

19. The method of claim **13** wherein the optical signal comprises a multi-level quadrature amplitude modulation (QAM) signal, a discrete multi-toned (DMT) modulation signal, an orthogonal frequency division multiplexing (OFDM), or a phase-shift keying (PSK) signal.

20. The method of claim 13 wherein the digital signal vector comprises data representing a single polarization modulation or a dual-polarization modulation.

21. A method of operating an optical communication system, the method comprising:

providing, by an optical transmitter configured, optical transmissions over an optical network;

receiving, by an optical receiver, an optical signal from the optical network;

generating, by the optical receiver, an analog signal vector representing the optical signal;

converting, an analog front-end of a transceiver coupled to the optical transmitter and the optical receiver, the analog signal vector into a digital signal vector, wherein the digital signal vector comprises a digital representation of an in-phase (I) component and a quadrature-phase (Q) component of the optical signal; and

generating, by a digital signal processing circuit of the transceiver, signal data representing a signal constellation of the digital signal vector;

wherein generating the signal data comprises

generating, by an adaptive gain equalizer of the digital signal processing circuit, transformed signal data by compensating the signal data for distortion of the signal constellation,

generating, by the adaptive gain equalizer, an estimate of an angular tilt of the signal constellation, and

compensating, by the adaptive gain equalizer, the signal data based on the estimate of the angular tilt.

22. The method of claim 21 wherein generating the estimate of the angular tilt comprises generating, by the adaptive gain equalizer, the angular tilt based on a sum of a plurality of cross-correlations of I and Q components of the signal constellation.

23. The method of claim 22 wherein the sum of the plurality of cross-correlations is computed over a moving window of data samples obtained from the digital signal vector.

24. The method of claim 21 wherein generating the estimate of the angular tilt further comprises iteratively revising, by the adaptive gain equalizer, the estimate of the angular tilt until I and Q components of the transformed signal data are substantially uncorrelated.

25. The method of claim 24 wherein iteratively revising the estimate of the angular tilt comprises iteratively revising, by the adaptive gain equalizer, the estimate of the angular tilt based on a step gain, wherein the step gain changes based on a number of times the angular tilt has been estimated.

26. The method of claim 21 wherein generating the transformed signal data comprises generating, by the adaptive gain equalizer, the transformed signal data based on a transformation matrix that includes the estimate of the angular tilt.

27. The method of claim 26 wherein the transformation matrix is about equal to

$$\frac{1}{\cos^2\theta - \sin^2\theta}\begin{bmatrix} \cos\theta & -\sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix},$$

wherein θ is the estimate of the angular tilt.

28. The method of claim 21 further comprising processing, by the digital signal processing circuit, the signal data for at least one of feed forward equalization or carrier recovery prior to compensating the signal data for distortion of the signal constellation.

29. The method of claim 21 further comprising slicing, by a decision slicer, the transformed signal data.

30. The method of claim 21 wherein the distortion of the signal constellation comprises at least one of squeezing, shifting, or tilting.

31. The method of claim 21 wherein the optical signal comprises a multi-level quadrature amplitude modulation (QAM) signal, a discrete multi-toned (DMT) modulation signal, an orthogonal frequency division multiplexing (OFDM), or a phase-shift keying (PSK) signal.

32. The method of claim 21 wherein the digital signal vector comprises data representing a single polarization modulation or a dual-polarization modulation.

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